Induction of Engineered Residual Stresses Fields and Enhancement of Fatigue Life of High Reliability Metallic Components by Laser Shock Processing

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SPIE Photonics West

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High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications II

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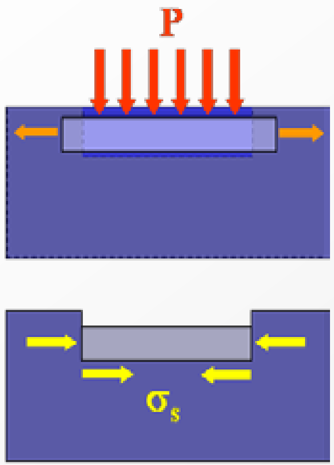
OUTLINE:

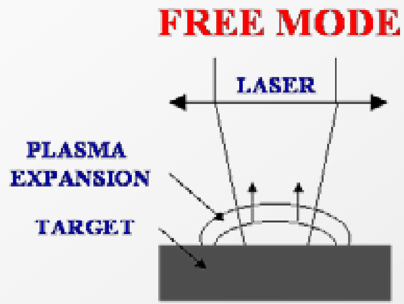
- Introduction
- Process Experimental Setup
  - Irradiation system
  - Experimental diagnosis system
- Experimental Procedure
- Experimental Results for Al2024-T351, Ti6Al4V and AISI 316L
  - Residual stresses
  - Tensile Strength
  - Fatigue Life
- Discussion and Outlook
  - Prospects for new technological applications of LSP

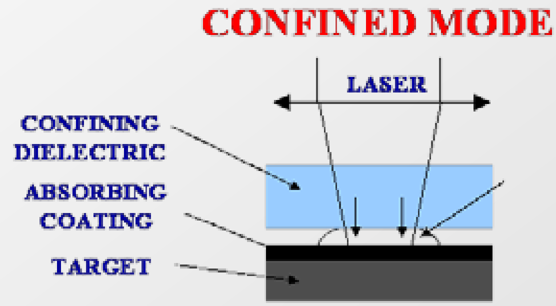
INTRODUCTION

- Laser Shock Processing (LSP) is being increasingly applied as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions, what makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.
- According to the inherent difficulty for the prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability coupled to a readily controllable experimental setup for a correct application of treatment parameters and an associate material properties characterization capability.
- In the present communication, the practical LSP treatment and associate specimens characterization capabilities developed at CLUPM (Spain) are presented along with selected results obtained in several relevant aerospace and nuclear industry alloys.

REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)

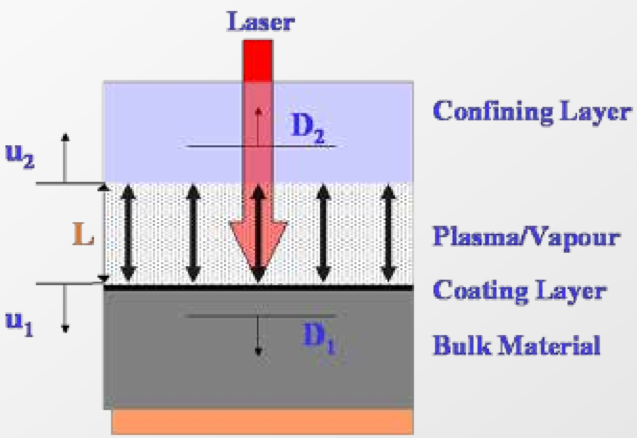


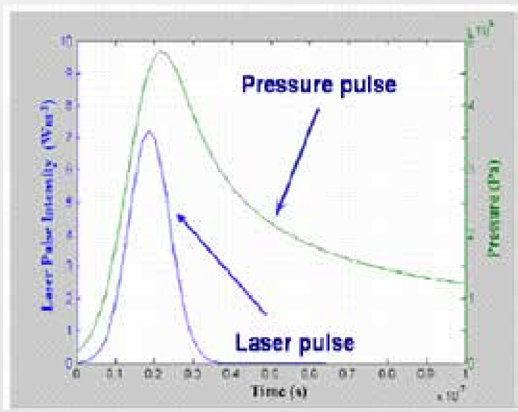


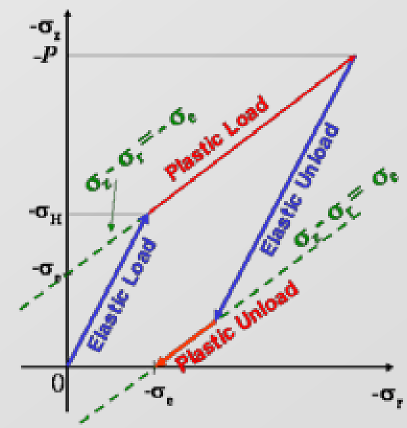


FREE PLASMA EXPANSION

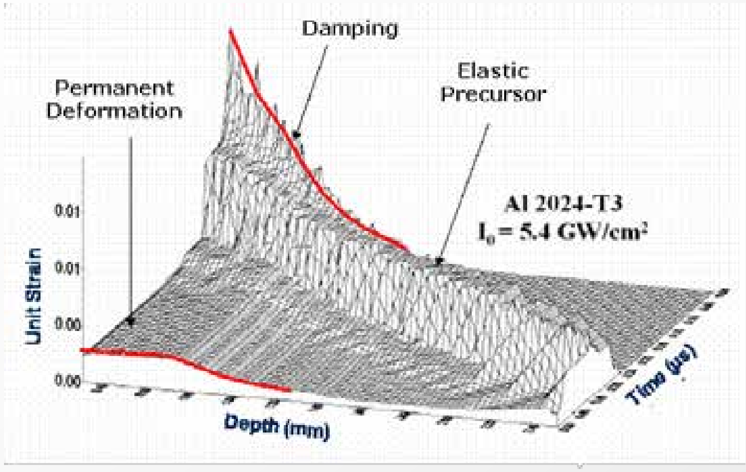
IMPROVED PRESSURE AND IMPULSION

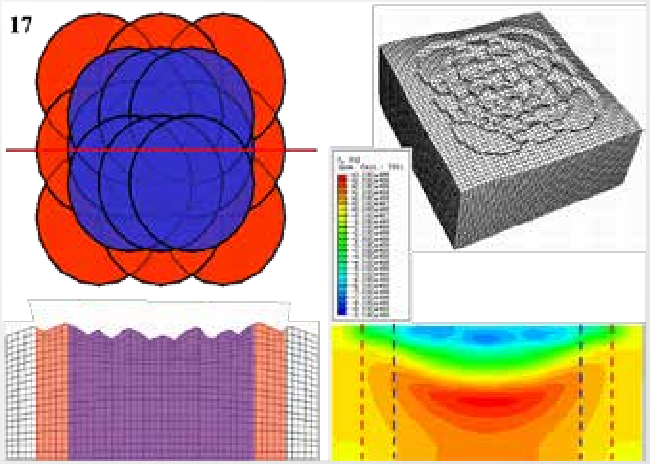


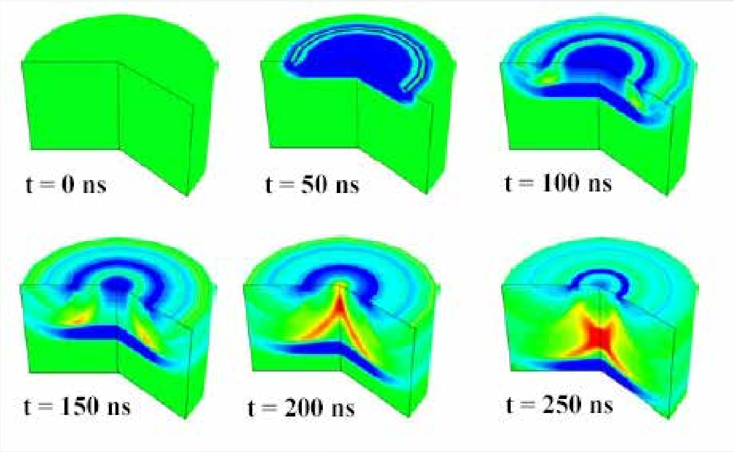


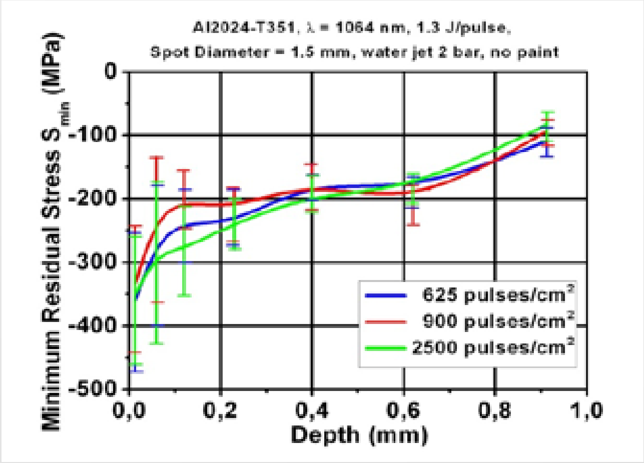


REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)

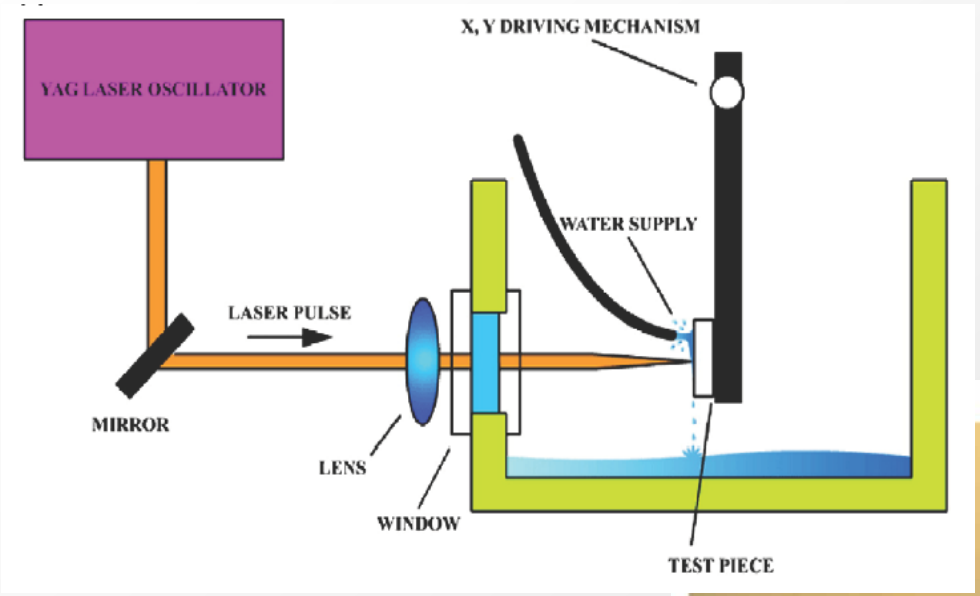


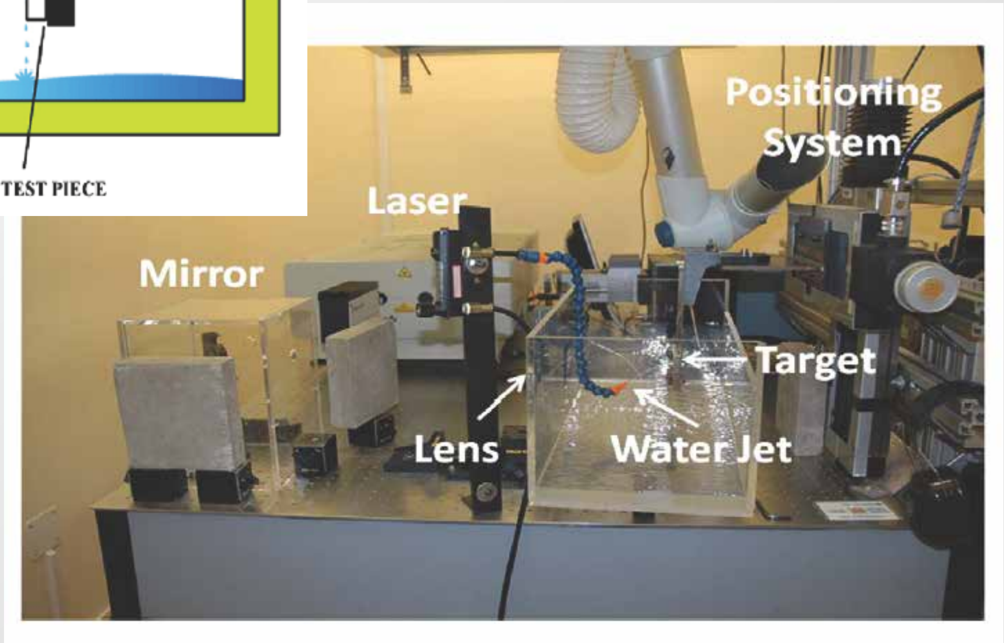






PROCESS EXPERIMENTAL SETUP





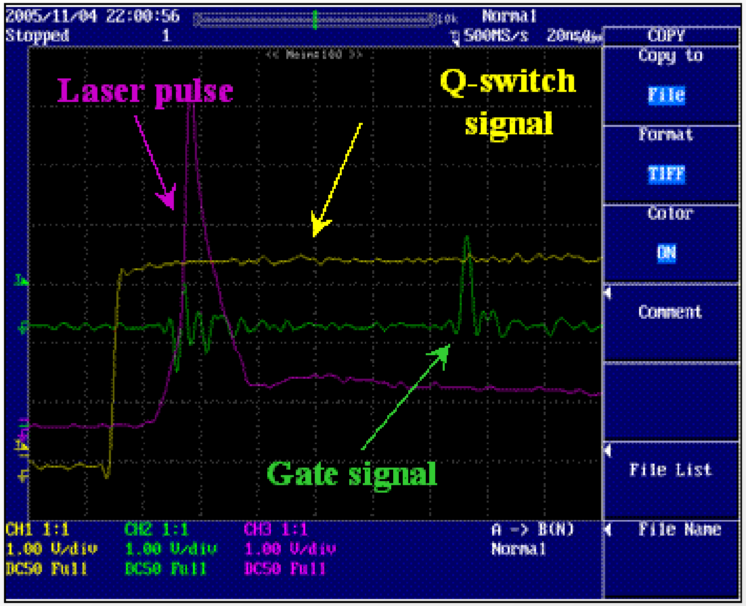
PROCESS EXPERIMENTAL SETUP

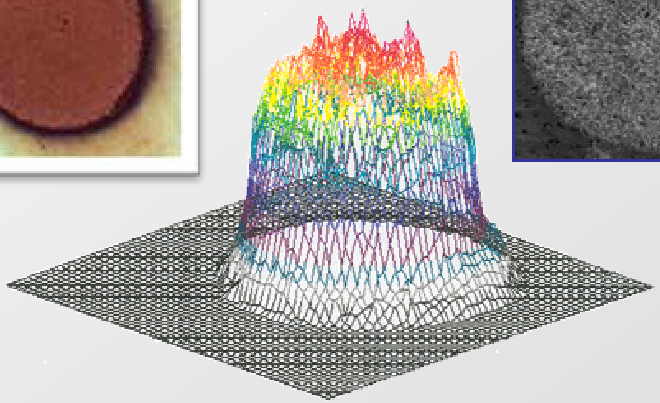
Spectra Physics Q-Switched Nd:YAG Laser

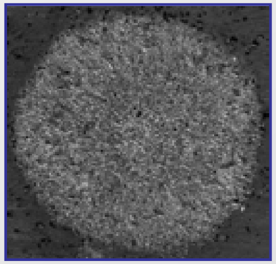
$$\begin{cases} \lambda = 1064\ \text{nm}\,; & E = 2{,}5\ \text{J/pulse} \\ \lambda = 532\ \text{nm}\,; & E = 1{,}4\ \text{J/pulse} \end{cases}$$

t = 10 ns; f = 10 Hz

PROCESS EXPERIMENTAL SETUP



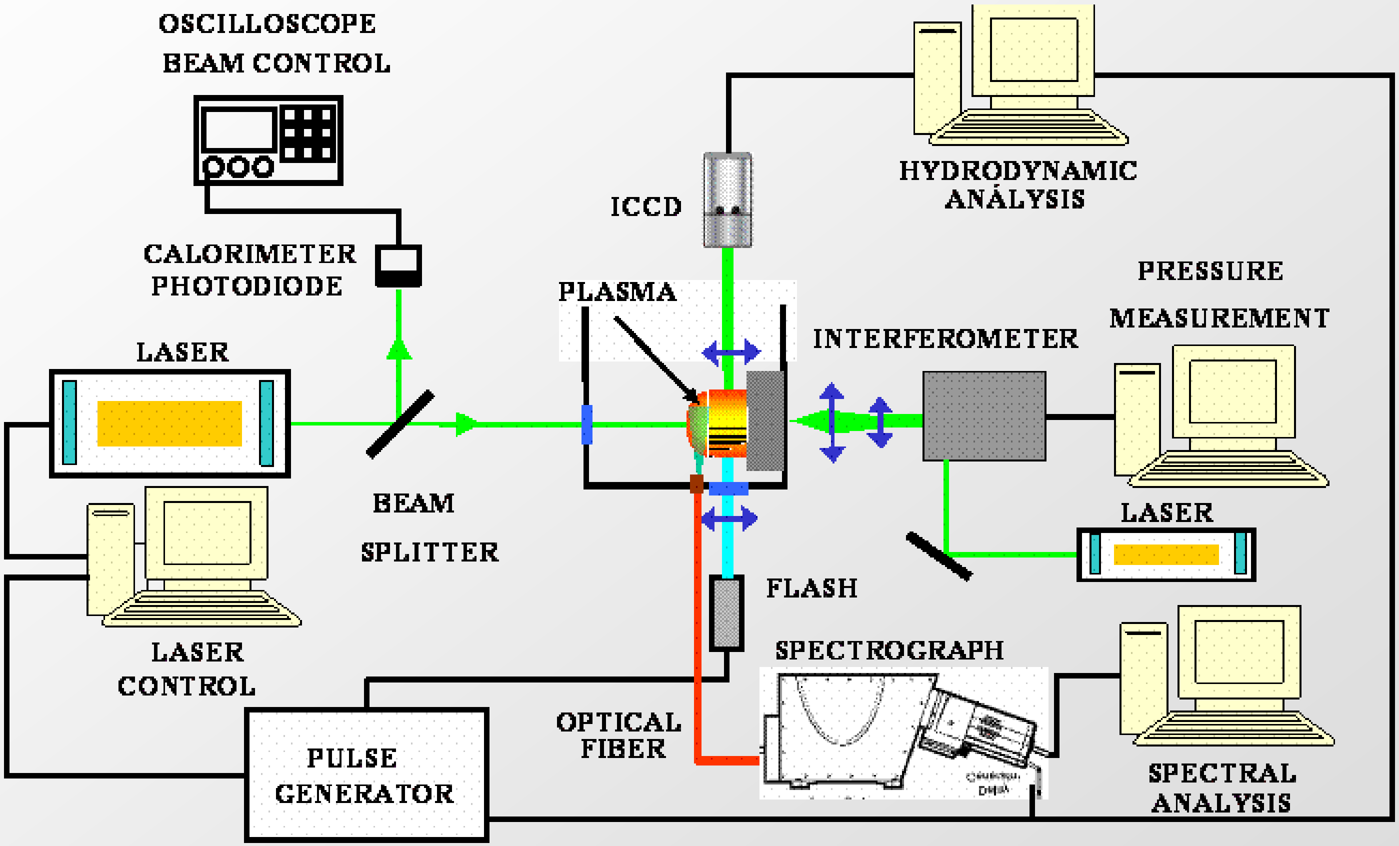




LSP TREATMENT PARAMETERS	
Laser wavelength (nm) ; Q-switched Nd:YAG	1064
Energy per pulse (J/pulse)	2,0
Pulse temporal width (ns)	≈ 9
Laser spot diameter (mm)	1.5
Ratio x-y pitch	1
Confining medium	Water jet ≈ 2 bar
Absorbing coating overlay	No

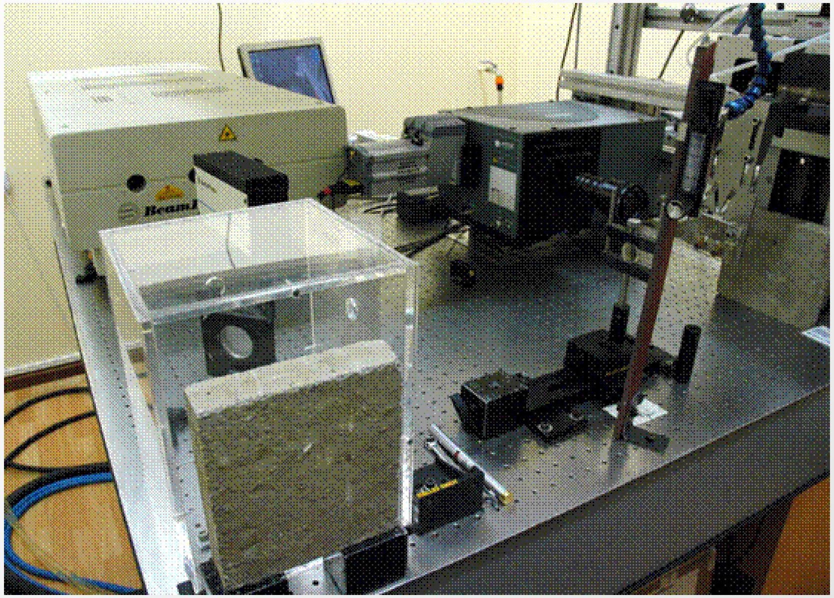
PROCESS EXPERIMENTAL SETUP

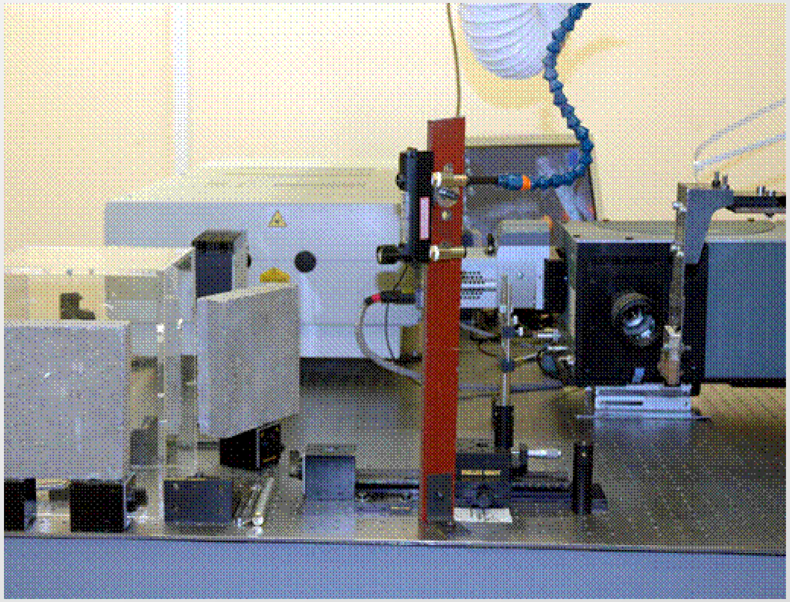
CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM



PROCESS EXPERIMENTAL SETUP

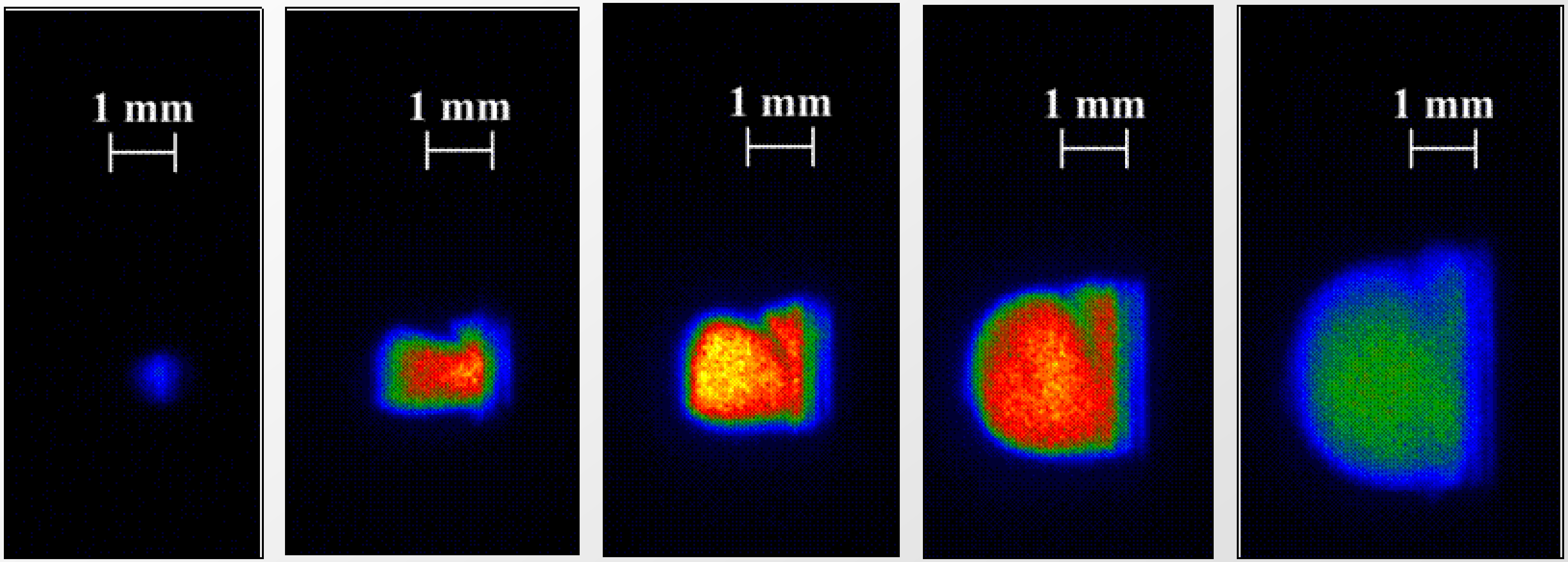
CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM





PROCESS EXPERIMENTAL SETUP

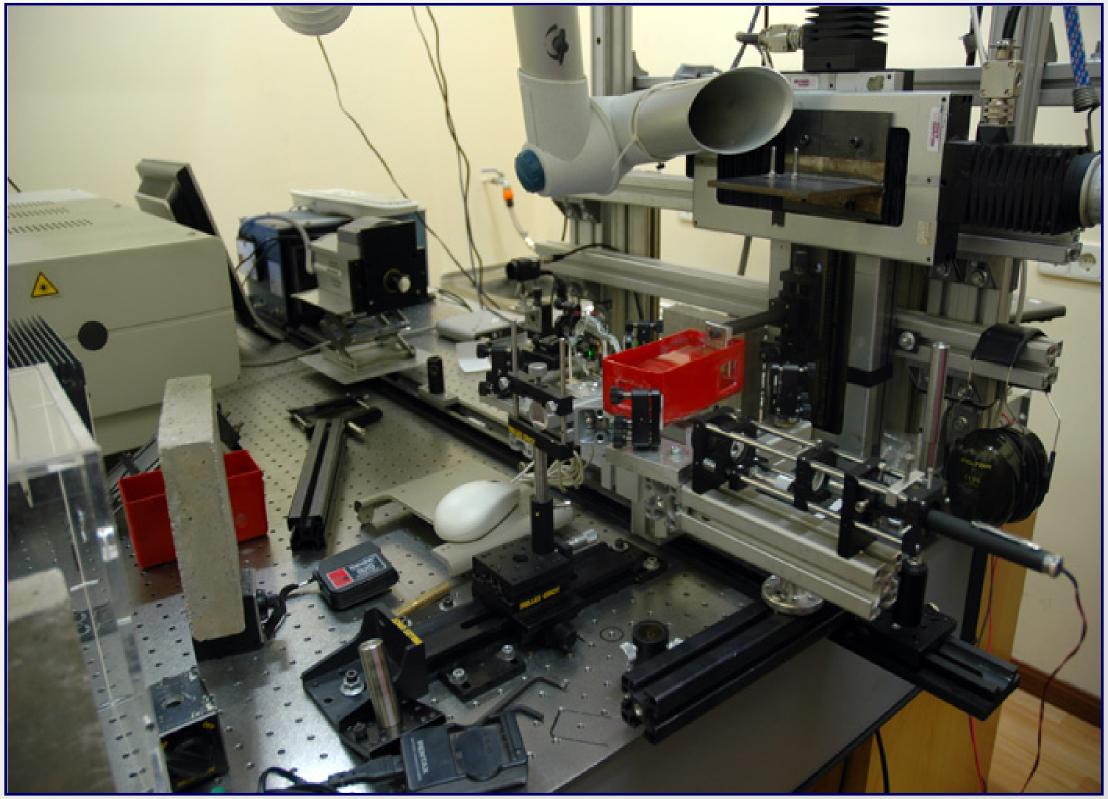
DIRECT IMAGING - HYDRODYNAMIC ANALYSIS



t = 10 ns | t = 25 ns | t = 50 ns | t =100 ns | t =200 ns

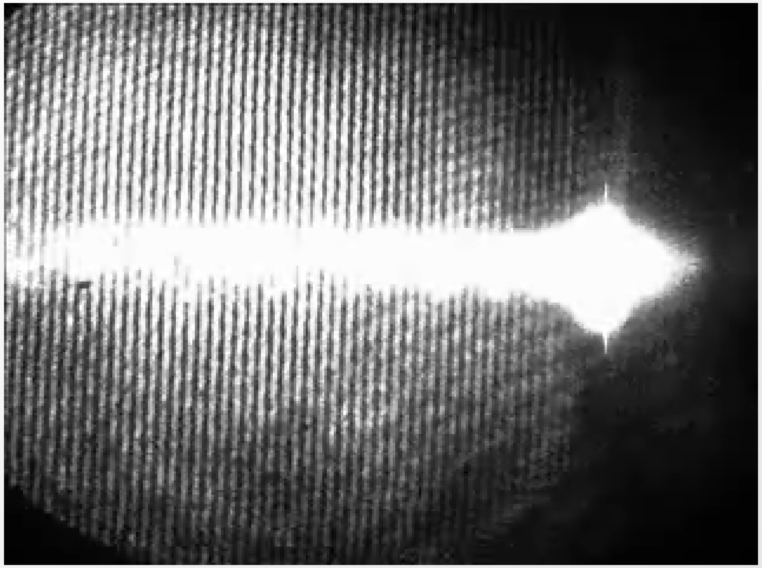
PROCESS EXPERIMENTAL SETUP

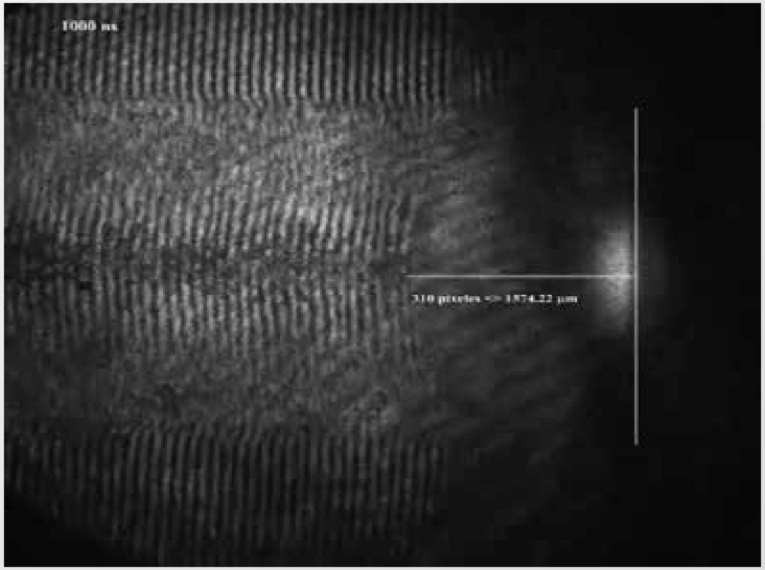
IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY



PROCESS EXPERIMENTAL SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY

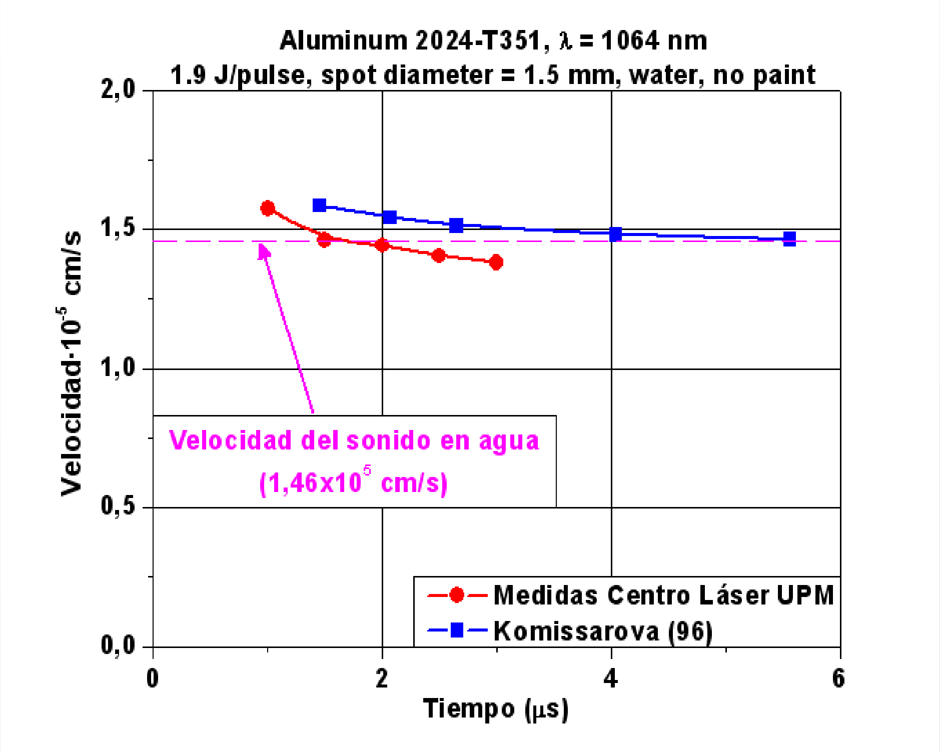




Martí-López, L. et al.: Appl. Optics, <u>48</u>, 3671-3680 (2009)

PROCESS EXPERIMENTAL SETUP

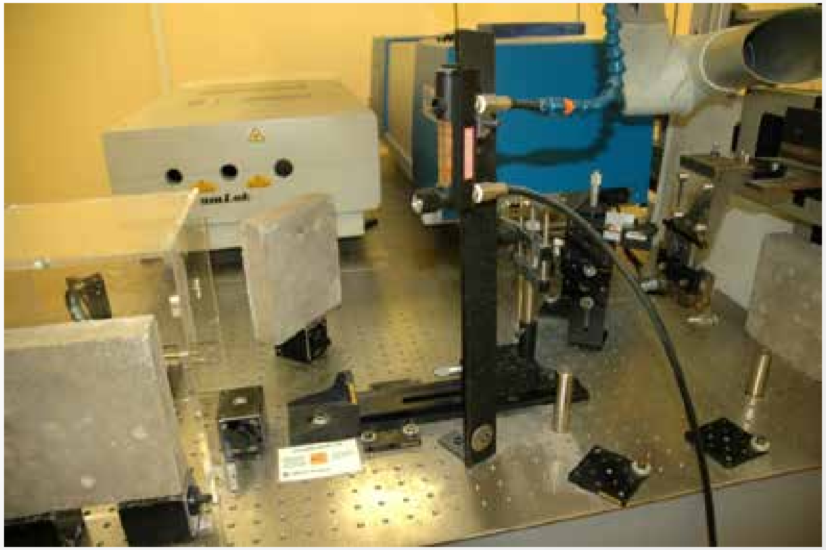
IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY

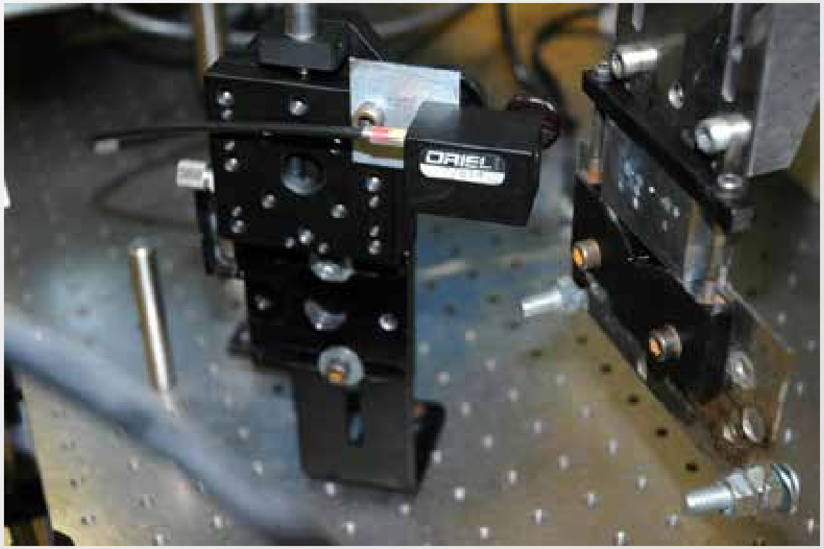


Martí-López, L. et al.: Appl. Optics, 48, 3671-3680 (2009)

PROCESS EXPERIMENTAL SETUP

EMISSION SPECTROSCOPY



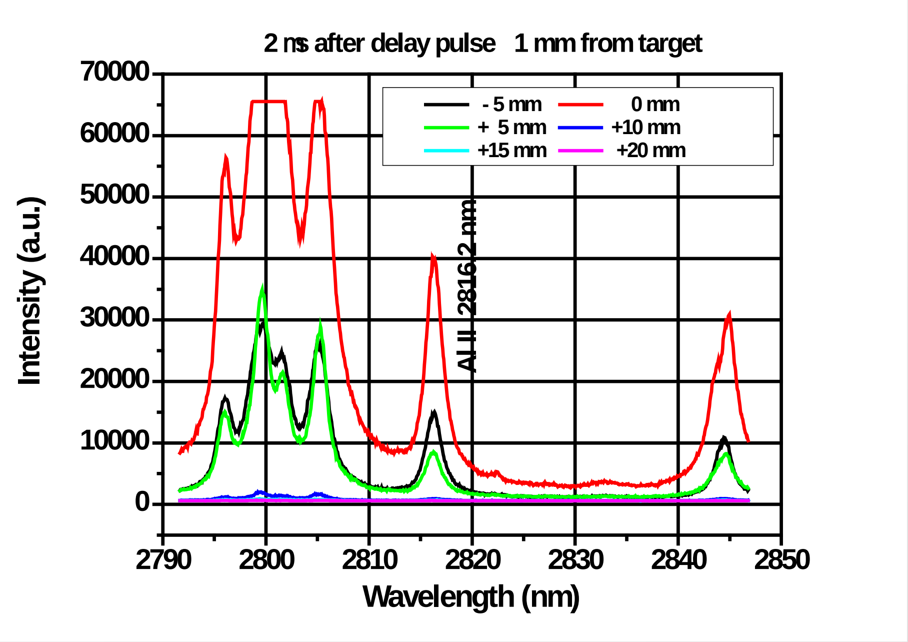


Spectroscopic system calibrated in wavelength with Hg lamp and in intensity with Deuterium lamp

PROCESS EXPERIMENTAL SETUP

EMISSION SPECTROSCOPY

Electron density determination via Stark effect of Al II line at 2816,2 nm:

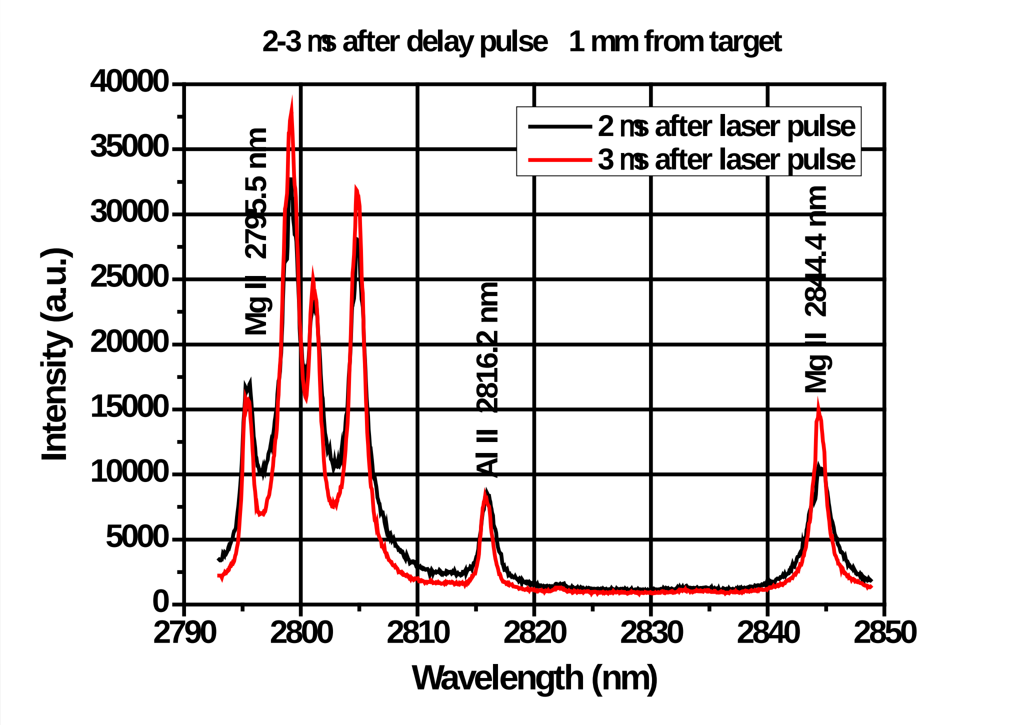


		Delay from laser pulse	
		2 μs	3 μs
Distance from target	1 mm	20.4 10^{16} cm^{-3}	2.4 10^{16} cm^{-3}
	6 mm	17.2 10^{16} cm^{-3}	2.0 10^{16} cm^{-3}

PROCESS EXPERIMENTAL SETUP

EMISSION SPECTROSCOPY

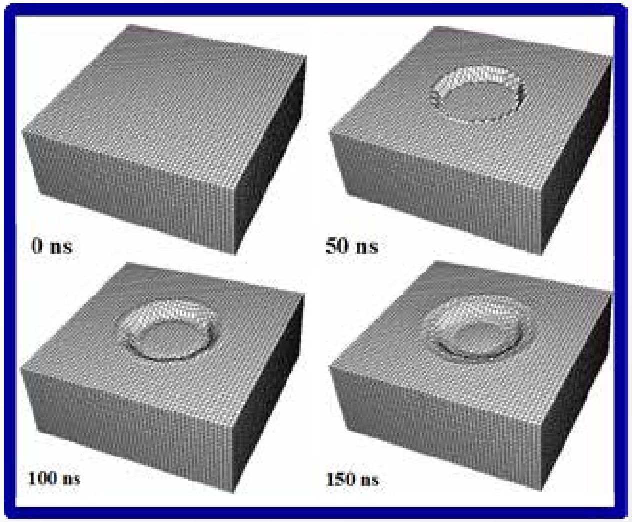
Electron temperature determination through Boltzmann plot of relative intensities of Mg II lines at 279.5528 nm, 280.2704 nm, 292.8633 nm and 293.6509 nm:

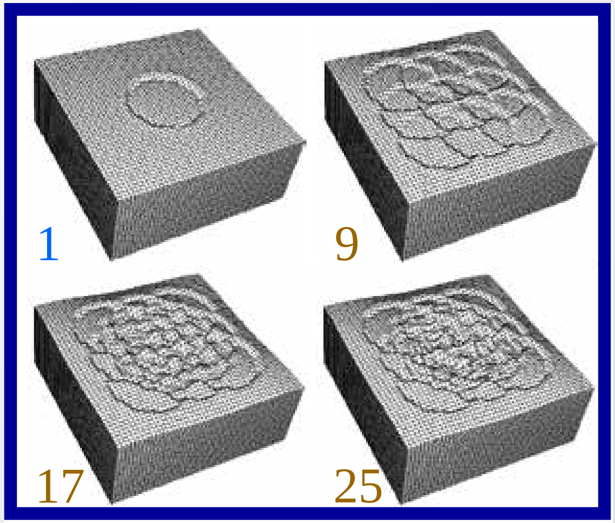


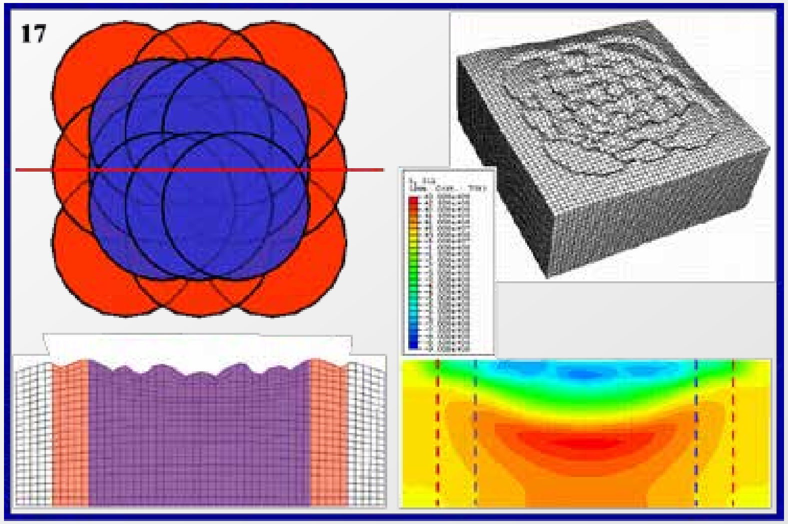
Preliminary electron temperature distributions in the range of 1.0-1.5 eV (i.e. @11 600 - 17 400 K) were found close to the target 2-3 ms after laser shut-down

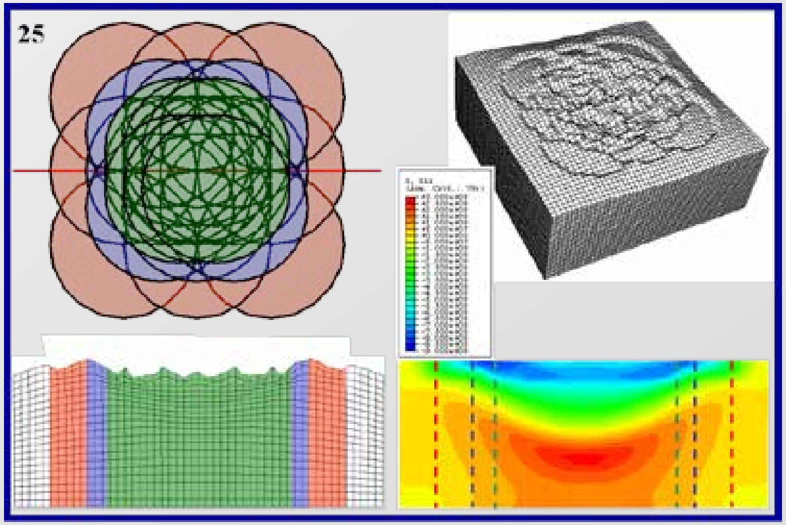
PROCESS EXPERIMENTAL SETUP

EXPERIMENTAL PROCEDURE

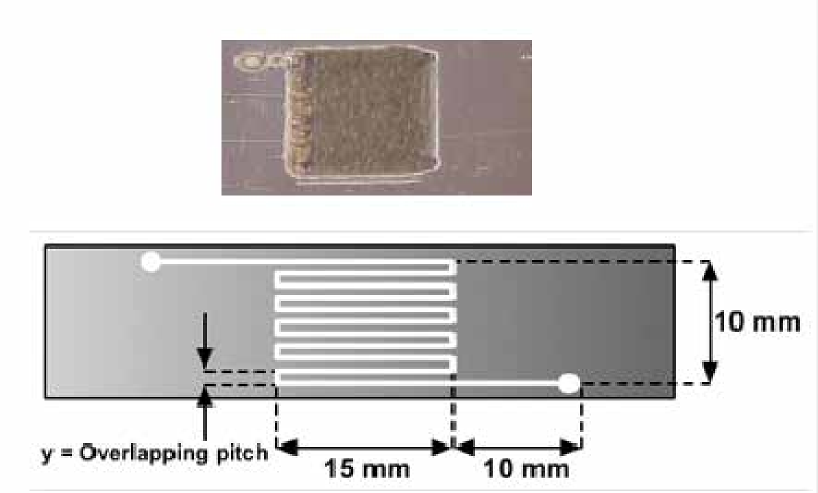








EXPERIMENTAL PROCEDURE



$$\text{Equivalent Overlapping Density} \equiv \text{EOD} = \frac{\text{N}^{\text{o}}\text{ of pulses}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\,\frac{y}{\Delta y}}{\Delta s} = \frac{\frac{x}{d}\,\frac{y}{d}}{xy} = \frac{1}{d^2}$$

$$\text{Equivalent Energy Density} \equiv \text{EED} = \frac{\text{N}^{\text{o}}\text{ of pulses} \times \text{Pulse Energy}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\,\frac{y}{\Delta y}E}{\Delta s} = \frac{\frac{x}{d}\,\frac{y}{d}E}{xy} = \frac{E}{d^2}$$

$$\text{Equivalent local overlapping factor} \equiv \text{ELOF} = \frac{\text{N}^{\text{o}}\text{ of pulses} \times \text{Pulse Area}}{\text{Total treated surface}} = \frac{\frac{\pi}{4} f^2}{d^2} = \frac{\pi}{4}\left(\frac{f}{d}\right)^2$$

EXPERIMENTAL PROCEDURE

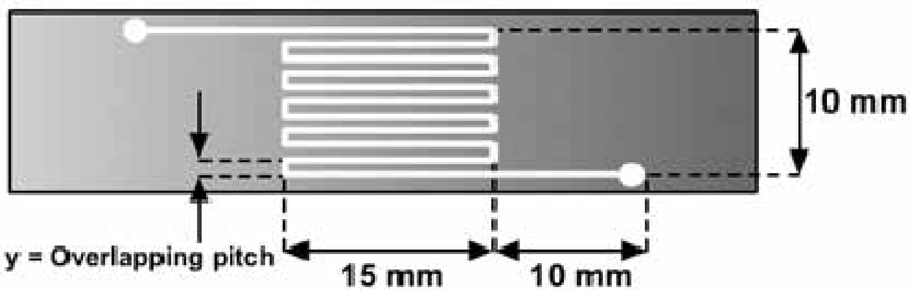


Table I: Relation between overlapping pitch and equivalent number of pulses per unit surface corresponding to the defined sweeping procedure.

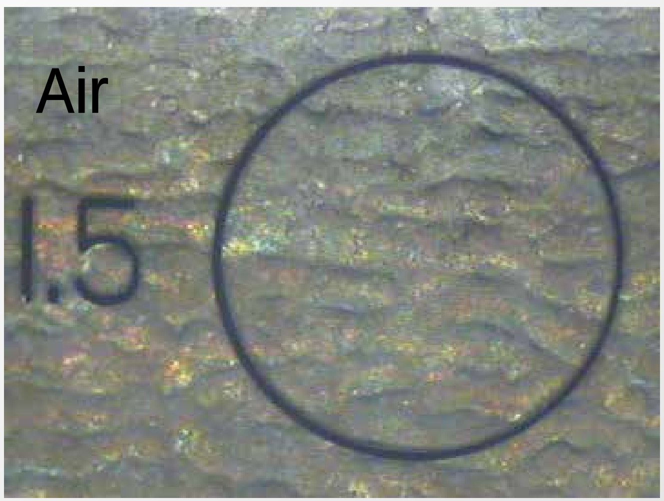
Overlapping pitch Y (mm)	Equivalent overlapping density (pulses/cm^2)
0.588	289
0,33	900
0.285	1225
0.2	2500
0,141	5000

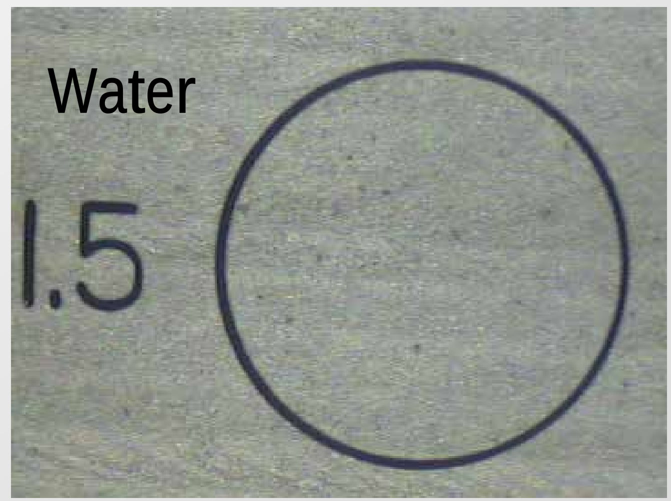
EXPERIMENTAL RESULTS

Material: Al2024 T3

Pulses: Æ=1,5 mm; t =10 ns; f=10 Hz;
E=1 J/pulse; I=1,41 GW/cm^2

Swept Area : 15x15 mm^2; 2500 pulses/cm^2





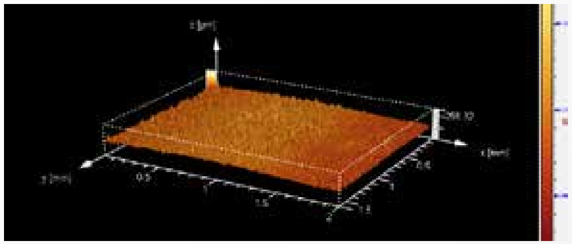
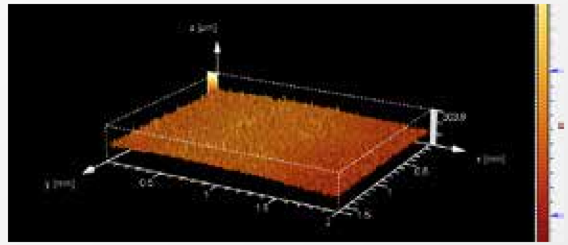
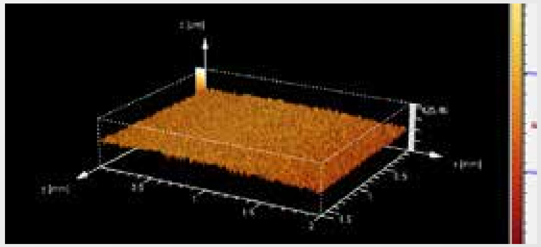
EXPERIMENTAL RESULTS

Reported Analysis

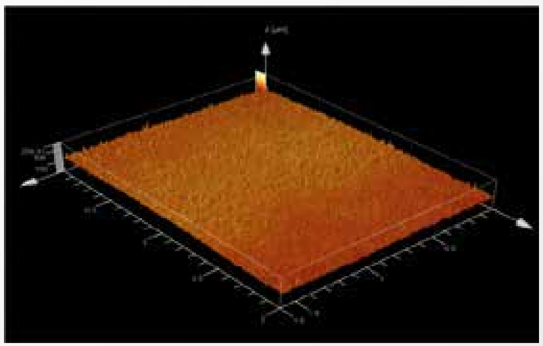
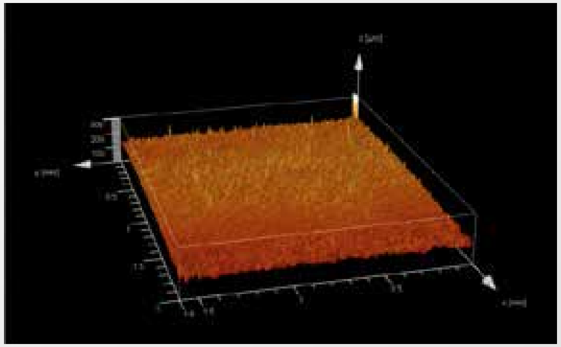
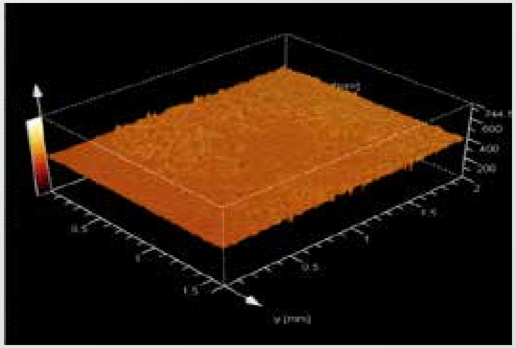
	Al2024-T351 30x20x8 mm^3	Ti6Al4V 30x20x10 mm^3
900 pulses/cm^2		
1600 pulses/cm^2		
2500 pulses/cm^2		
5000 pulses/cm^2		

EXPERIMENTAL RESULTS

Surface Roughness (Topographic Confocal microscopy): Al2024-T351

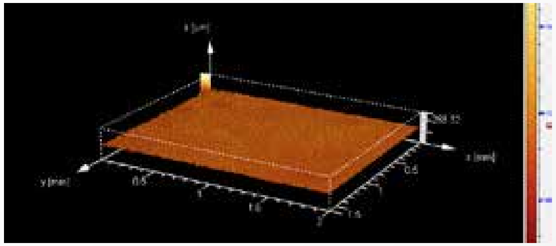
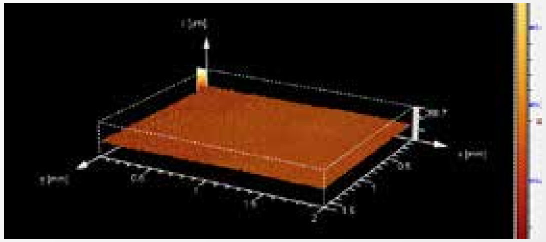
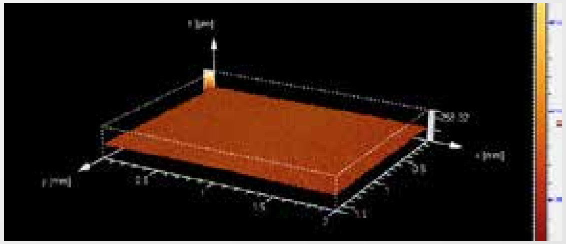
900 pulses/cm^2 | 1600 pulses/cm^2 | 2500 pulses/cm^2

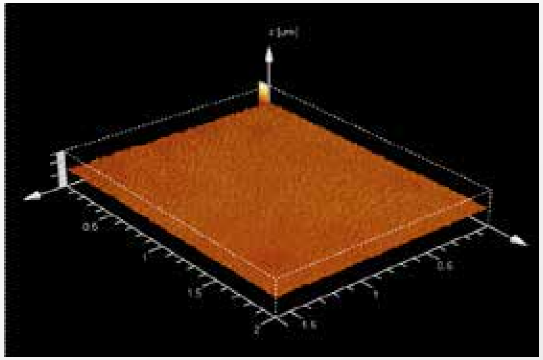
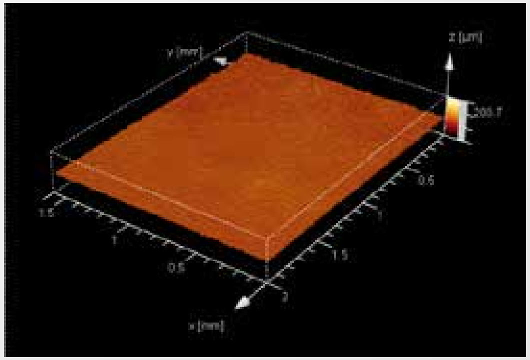
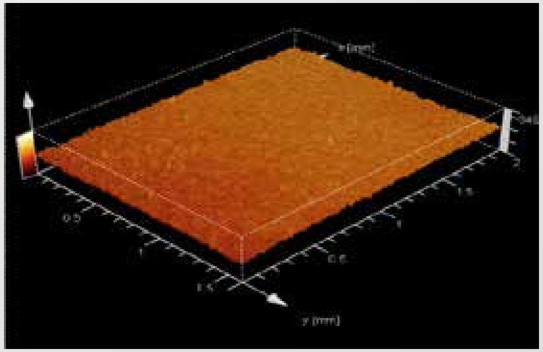
	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (mm)	7.96	5.23	4.82	4.96
<Dz>	----	10.30	20.00	26.82

EXPERIMENTAL RESULTS

Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

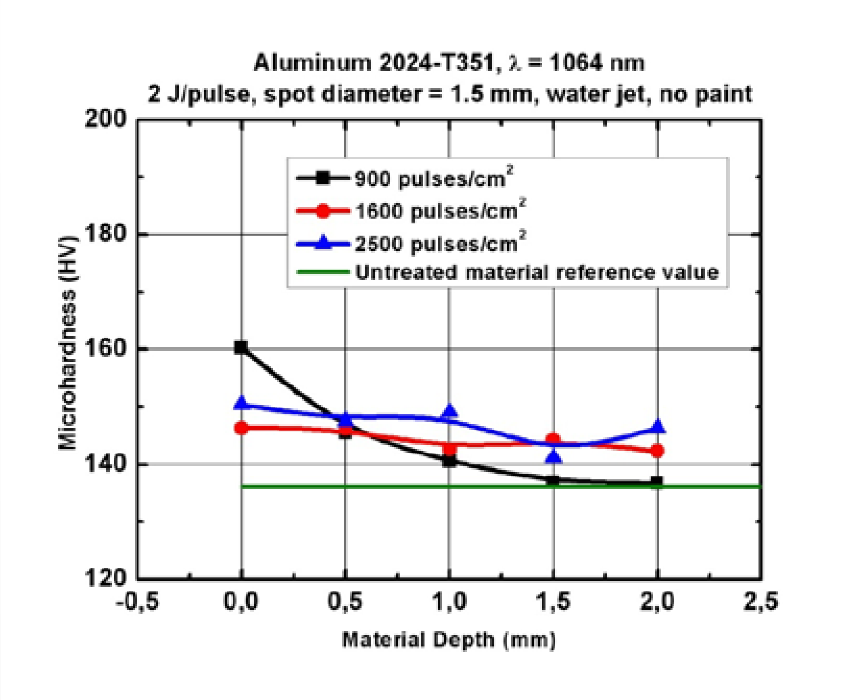
900 pulses/cm^2 | **2500 pulses/cm^2** | **5000 pulses/cm^2**

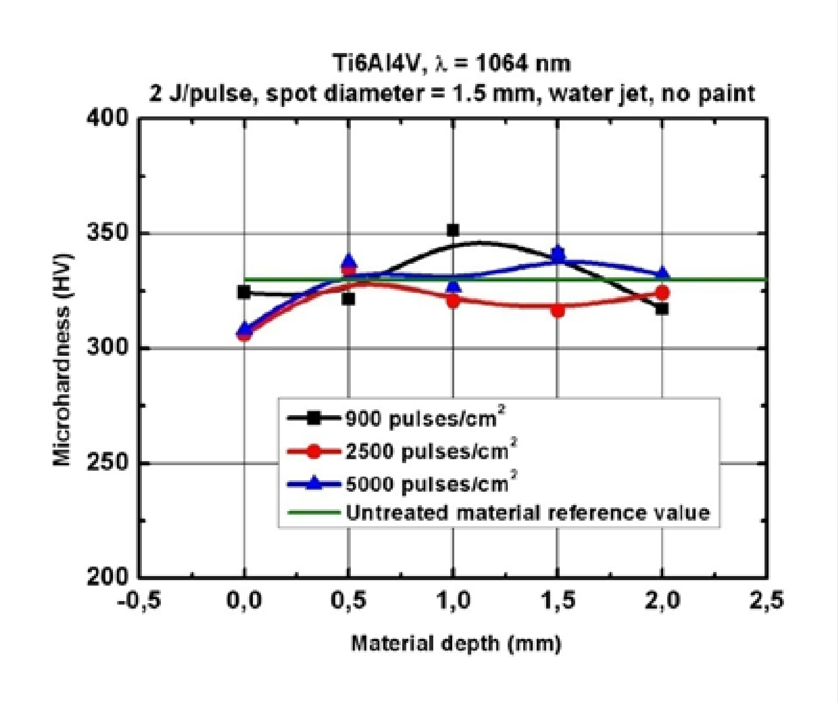




	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (mm)	9.98	3.62	3.87	3.87
<Dz>	----	2.81	7.40	5.80

EXPERIMENTAL RESULTS

Microhardness (HV)





Slight increase in microhardness in Al2024-T351
Higher for higher LSP treatement intensity

No apparent hardening effect in Ti6Al4V.

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

2–7 February 2013
The Moscone Center
San Francisco, California, USA

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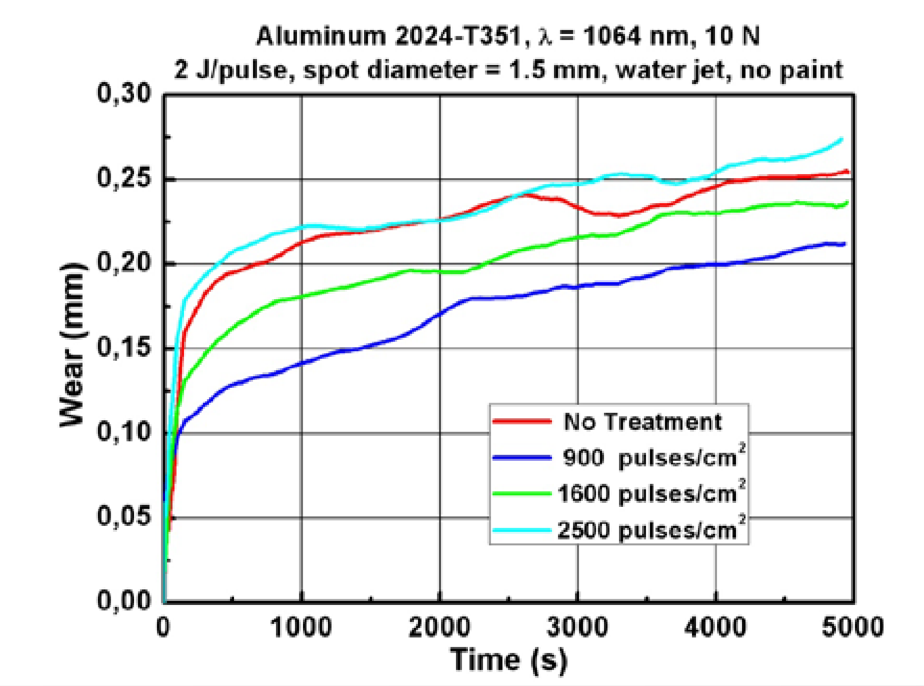
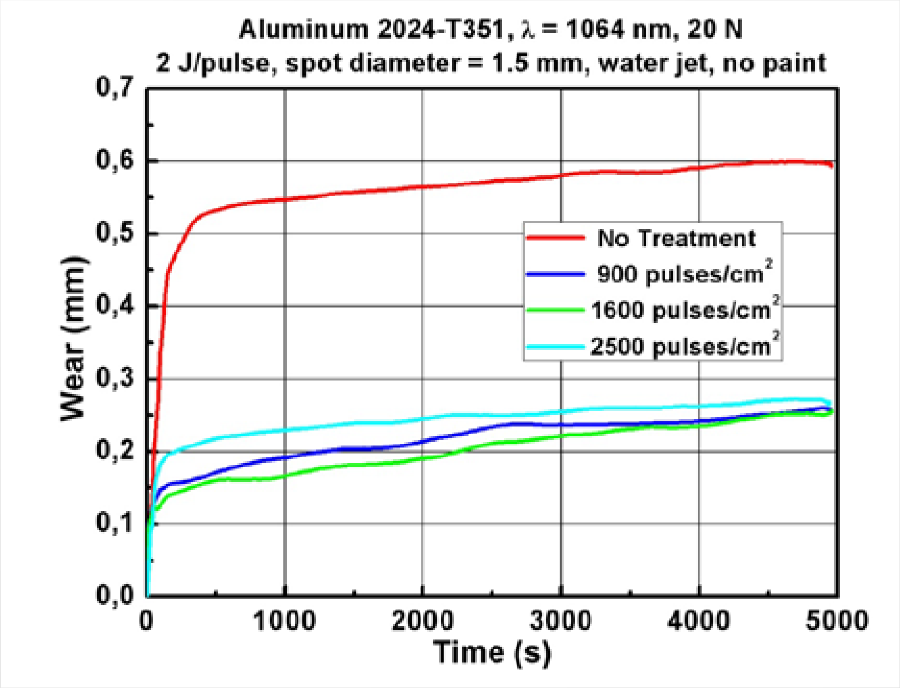
EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Al2024-T351





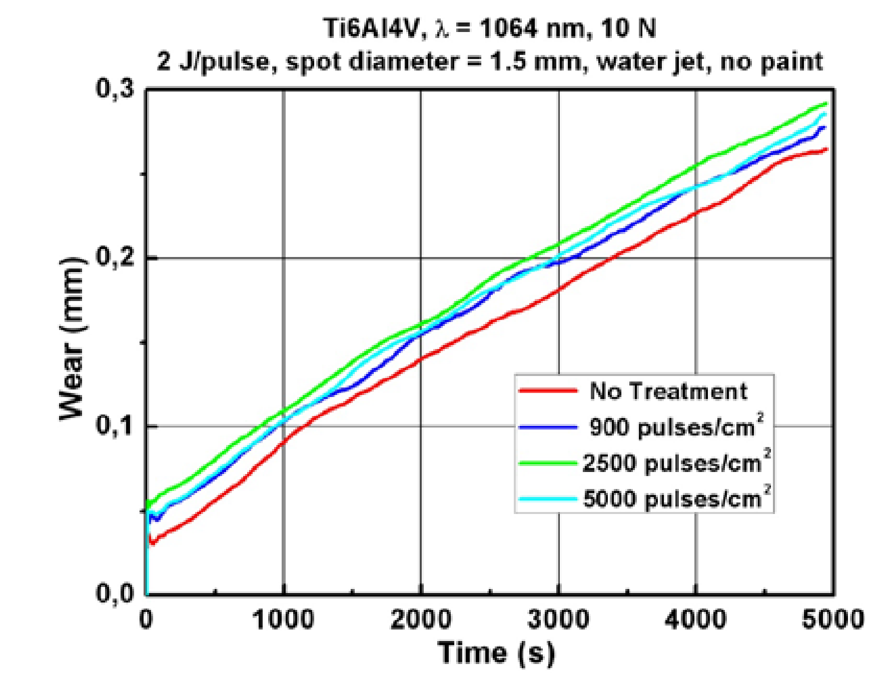
Slight wear improvement in Al2024-T351 at low loads

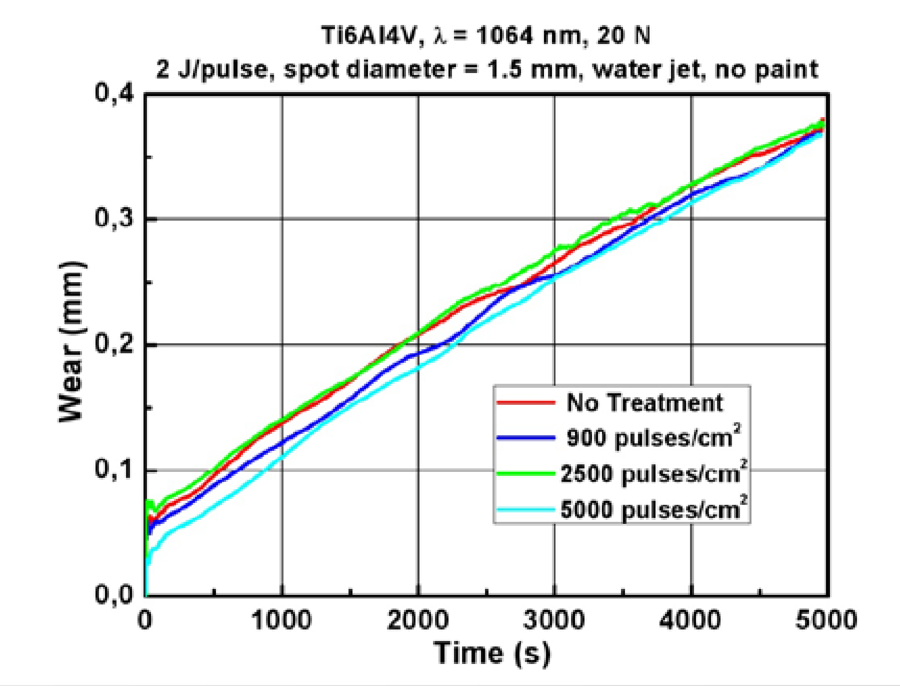
Considerable wear improvement in Al2024-T351 at moderate loads

EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Ti6Al4V

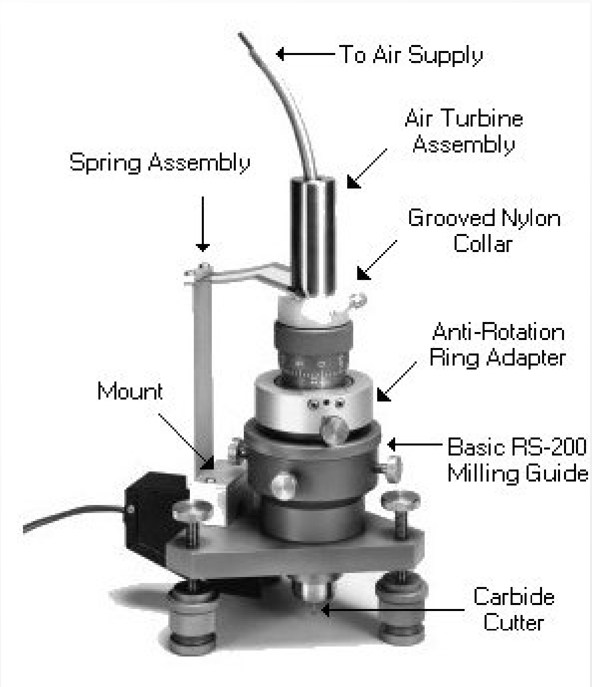


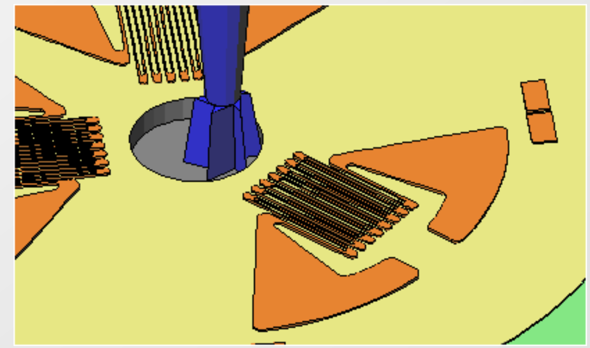


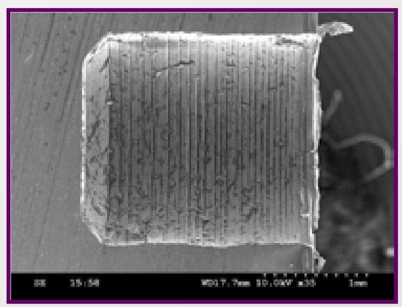
Slight negative wear impact in Ti6Al4V at low loads

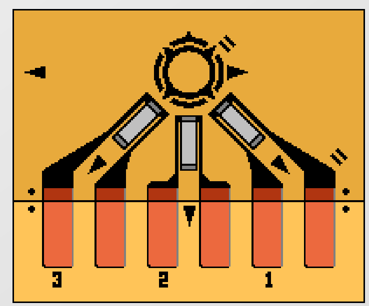
Inappreciable wear improvement in Ti6Al4V at moderate loads

Residual Stresses (According to ASTM E837-08)









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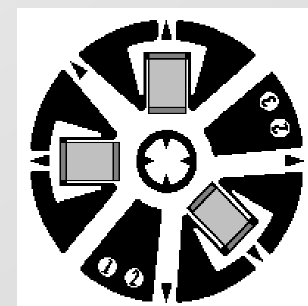
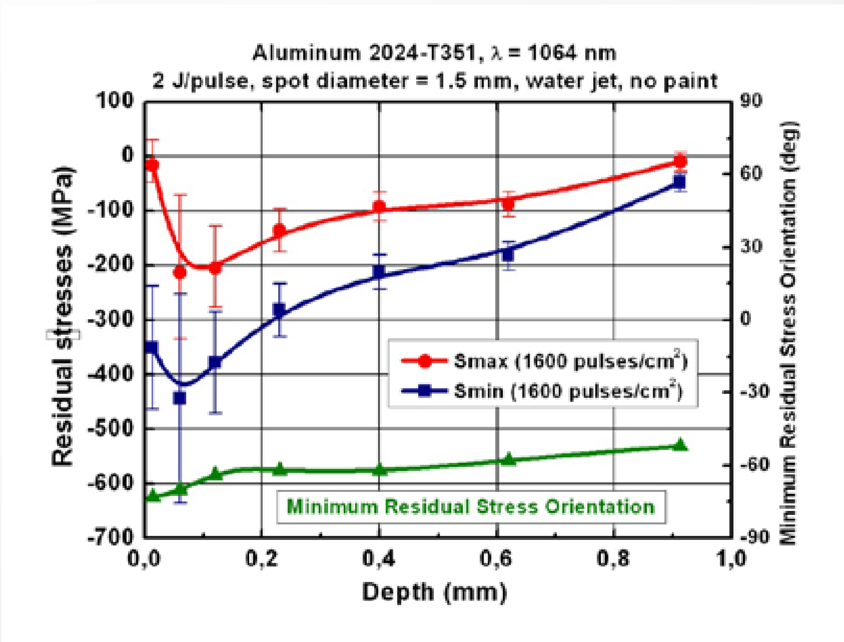


EA-XX-062RE-120

EXPERIMENTAL RESULTS

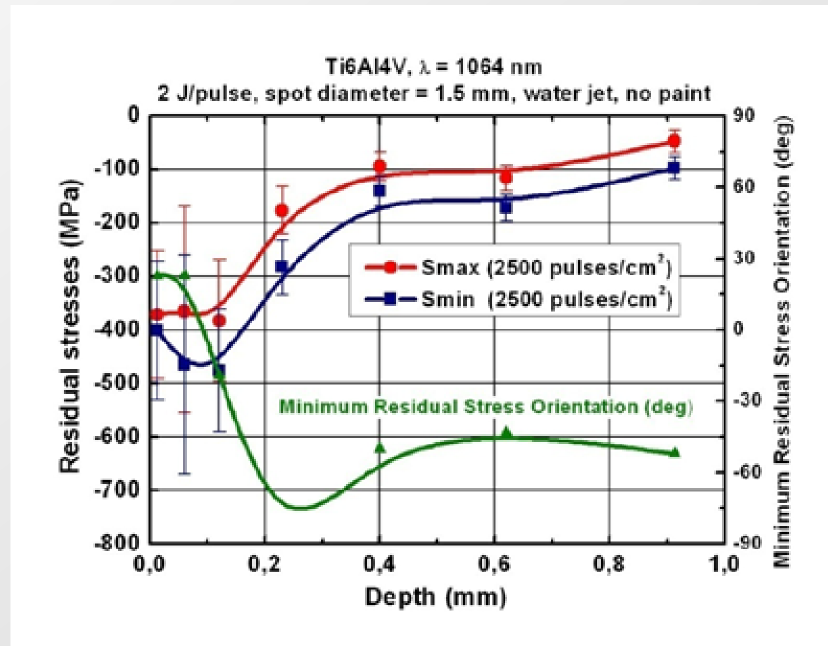
Residual Stresses (According to ASTM E837-08)

Al2024-T351



Relatively broad difference between S_{max} and S_{min} in Al2024-T351

Ti6Al4V

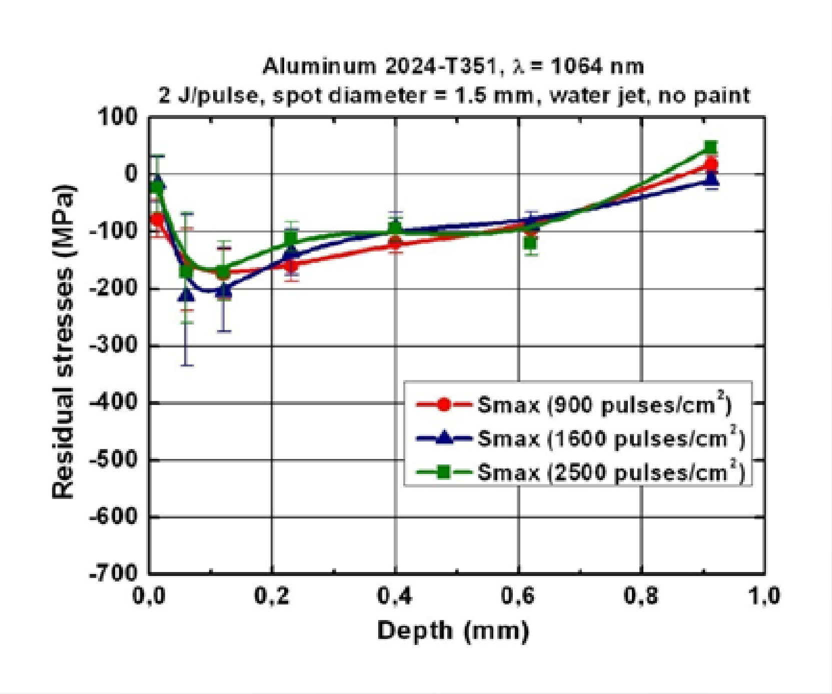


Relatively small difference between S_{max} and S_{min} in Ti6Al4V

EXPERIMENTAL RESULTS

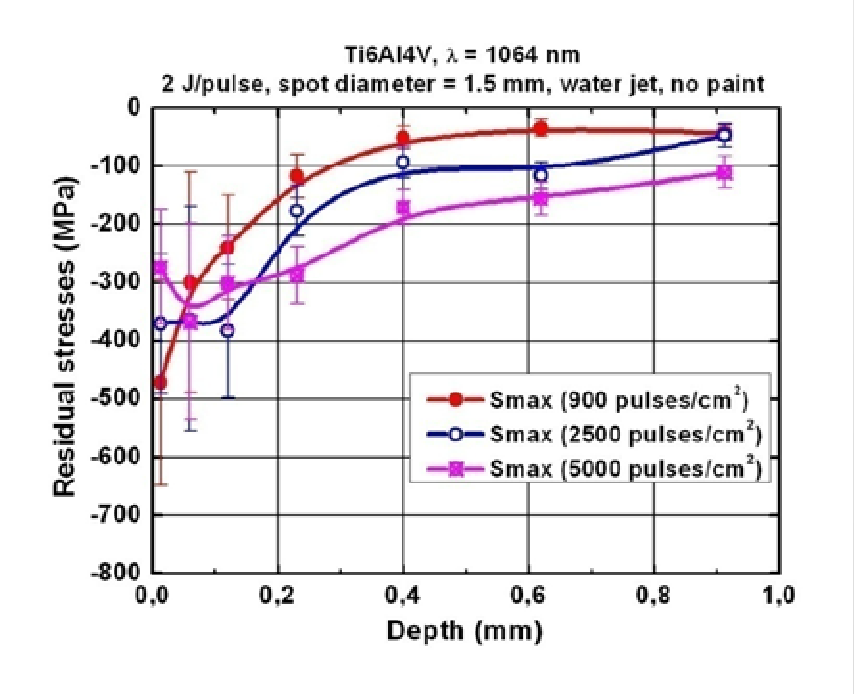
Residual Stresses (According to ASTM E837-08)

Al2024-T351



S_{max} in Al2024-T351 for different irradiation intensities

Ti6Al4V



S_{max} in Ti6Al4V for different irradiation intensities

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

2–7 February 2013
The Moscone Center
San Francisco, California, USA

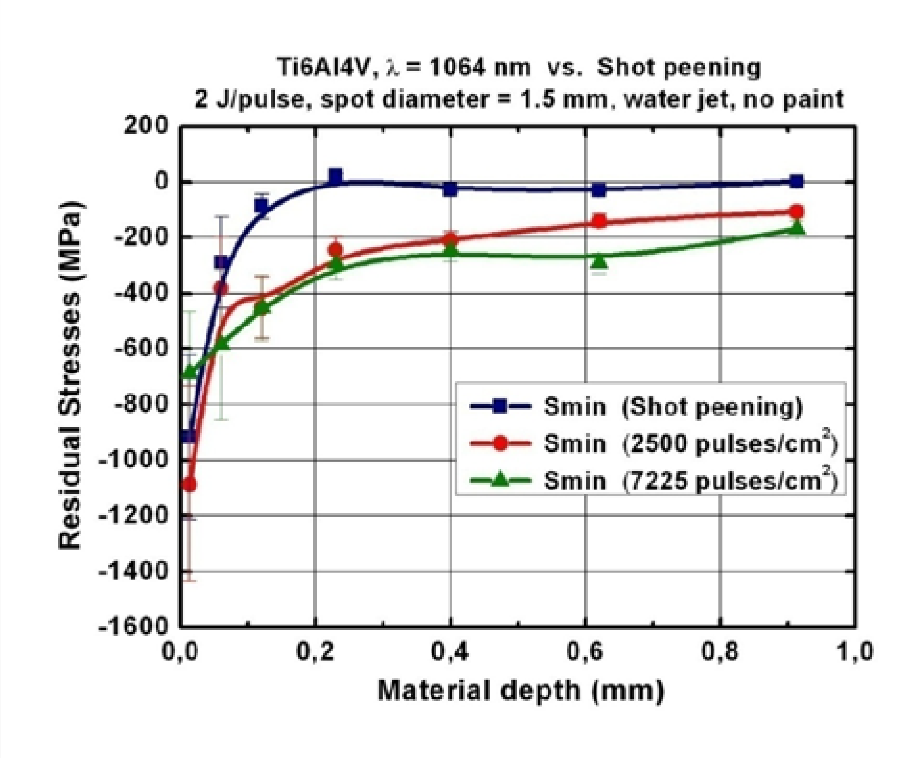
SPIE Photonics West

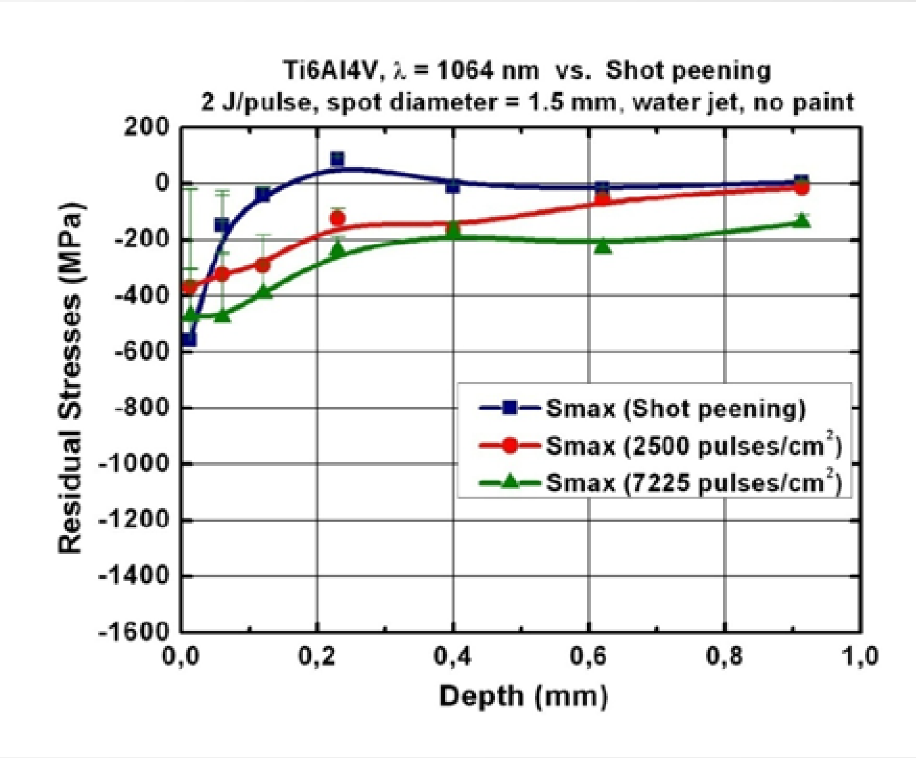
LASE
SPIE Photonics West

EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening





Substantial improvement in Residual Stresses Field in Ti6Al4V vs. to Shot Peening

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities

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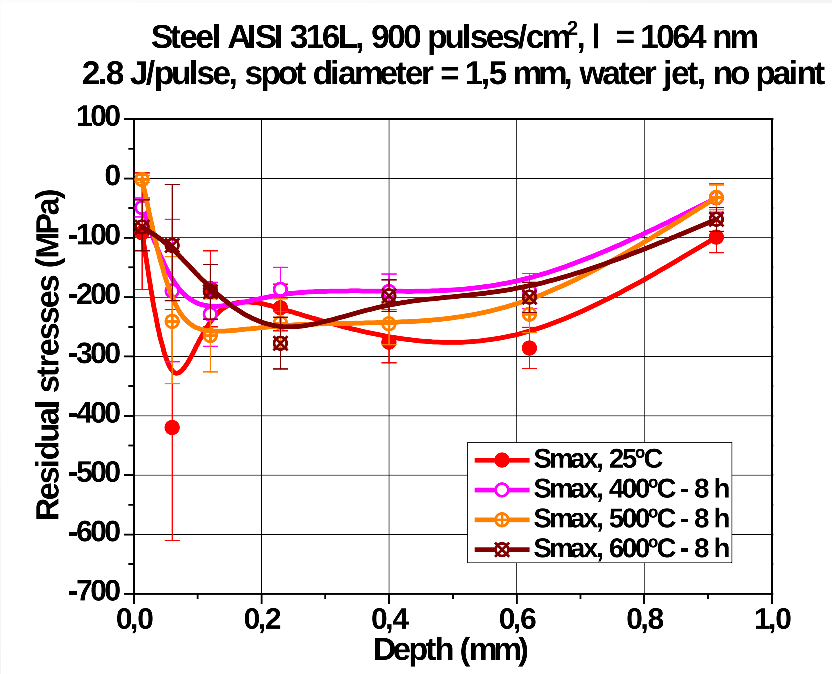
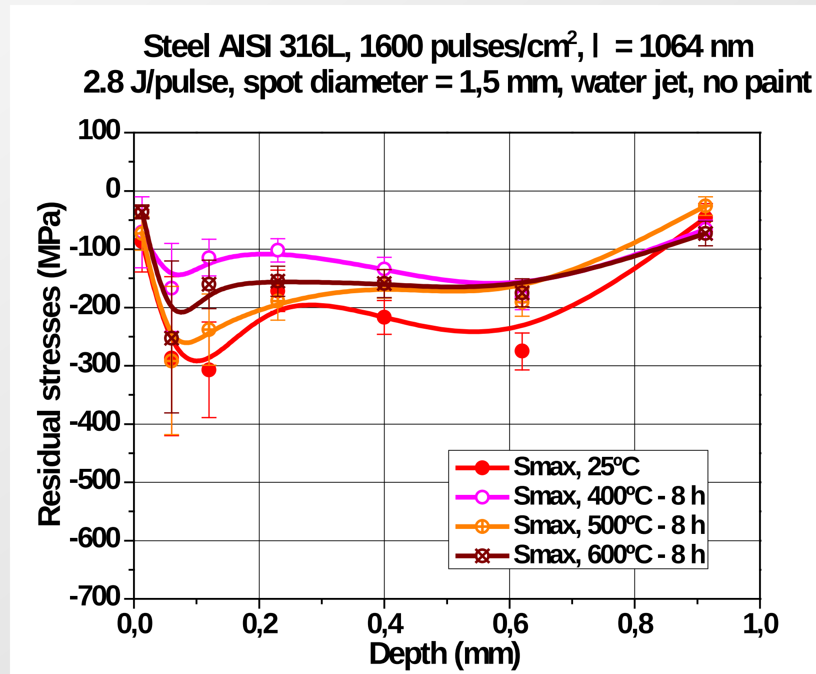
Residual Stresses Permanence upon Thermal Treatment

AISI 316L Steel

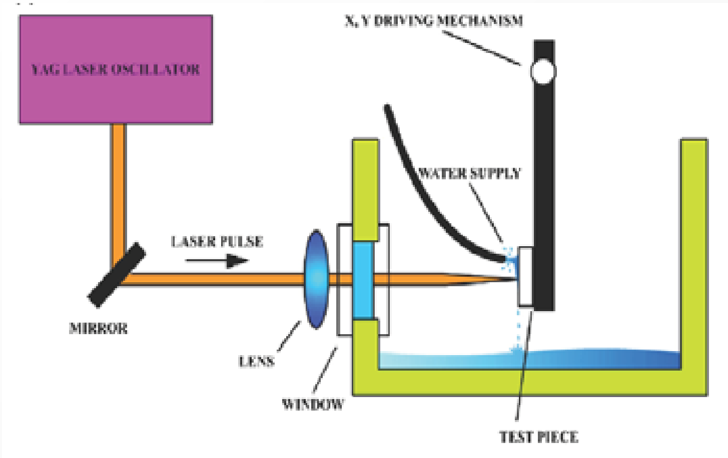


S_{max} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 900 pulses/cm^2 LSP Treatment Intensity



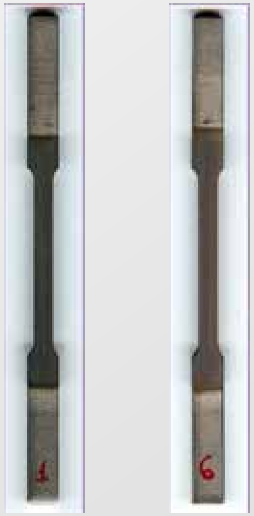
S_{max} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 1600 pulses/cm^2 LSP Treatment Intensity

EXPERIMENTAL RESULTS

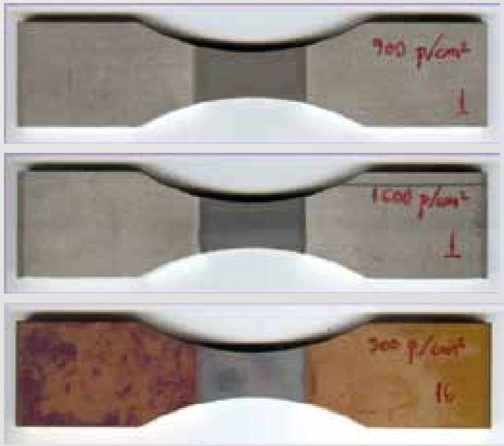


Process parameters	
Wavelength (nm)	1064
Frecuency (Hz)	10
Energy (J/pulse)	2.8
Pulse width (ns)	~ 9
Spot diameter (mm)	~ 1.5
Overlapping (pulses/cm^2)	900
	1600
Confining medium	Water jet
Absorbent coating	No

LSP Experimental setup at CLUPM



900 pul/cm^2 1600 pul/cm^2



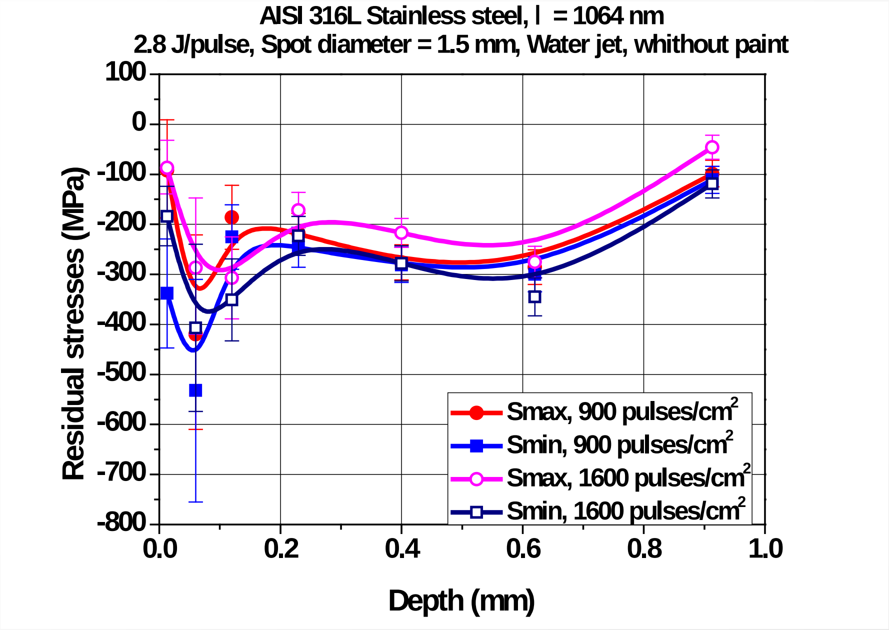
900 pulses/cm^2

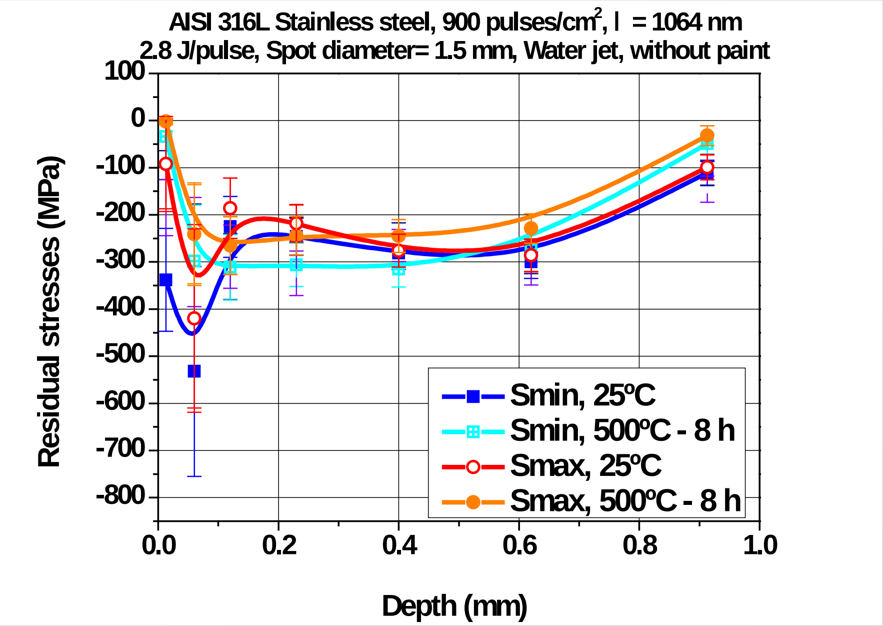
1600 pulses/cm^2

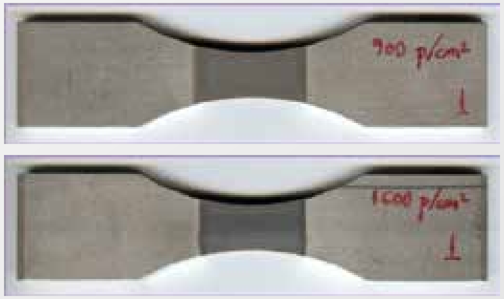
900 pulses/cm^2 + Heat treat.: 500 ˚C, 8h

EXPERIMENTAL RESULTS

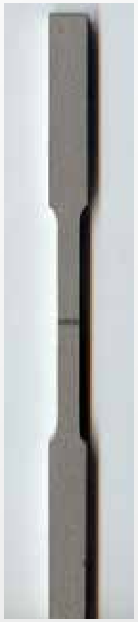
Residual Stresses:

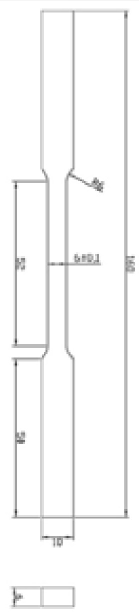




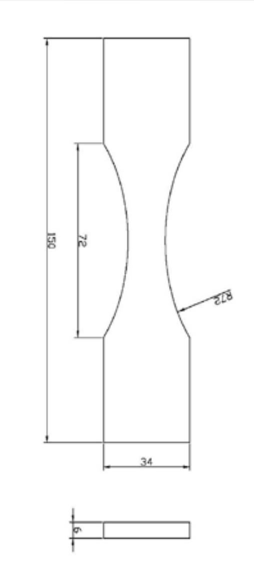


EXPERIMENTAL RESULTS





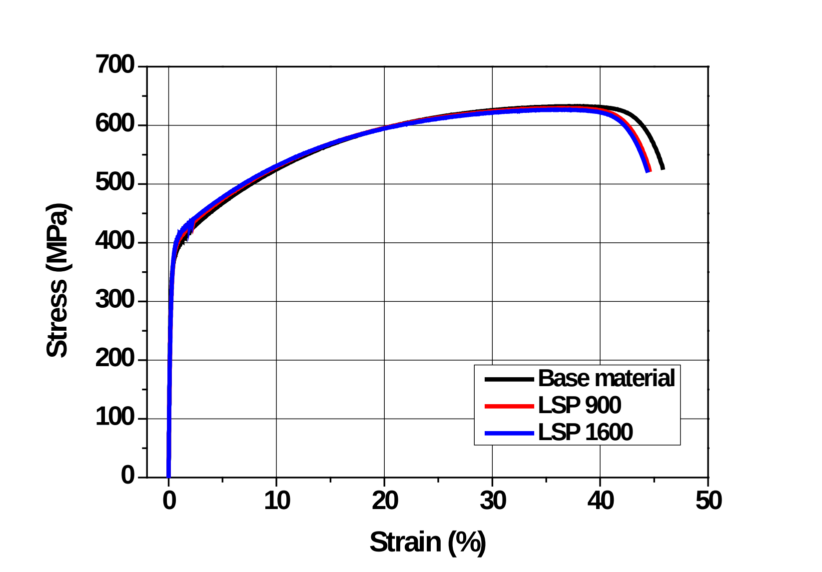
"Sub-size" Tensile Specimen
ASTM E 8M



"Bone" Fatigue Specimen
ASTM E 466

EXPERIMENTAL RESULTS

Tensile Tests:

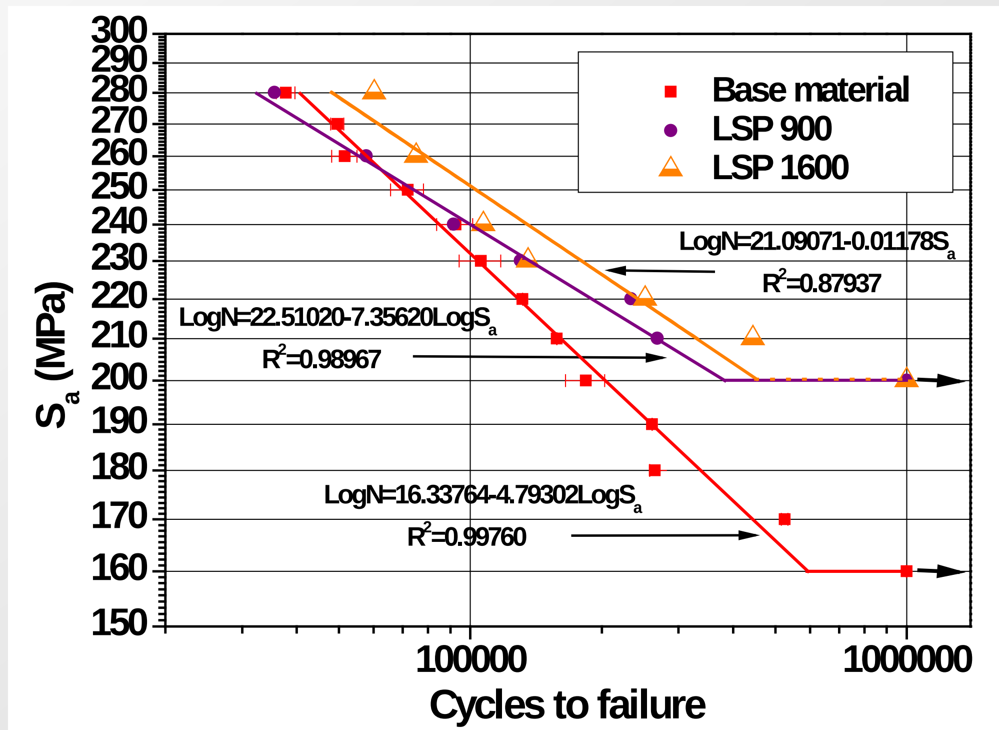


Property	Base material	LSP 900	LSP 1600
Young Modulus (GPa)	177.205	182.099	185.446
Engineering elastic limit (MPa)	355.410	356.390	359.930
Maximun tensile stress (MPa)	633.608	629.700	626.870

EXPERIMENTAL RESULTS

Fatigue Tests:

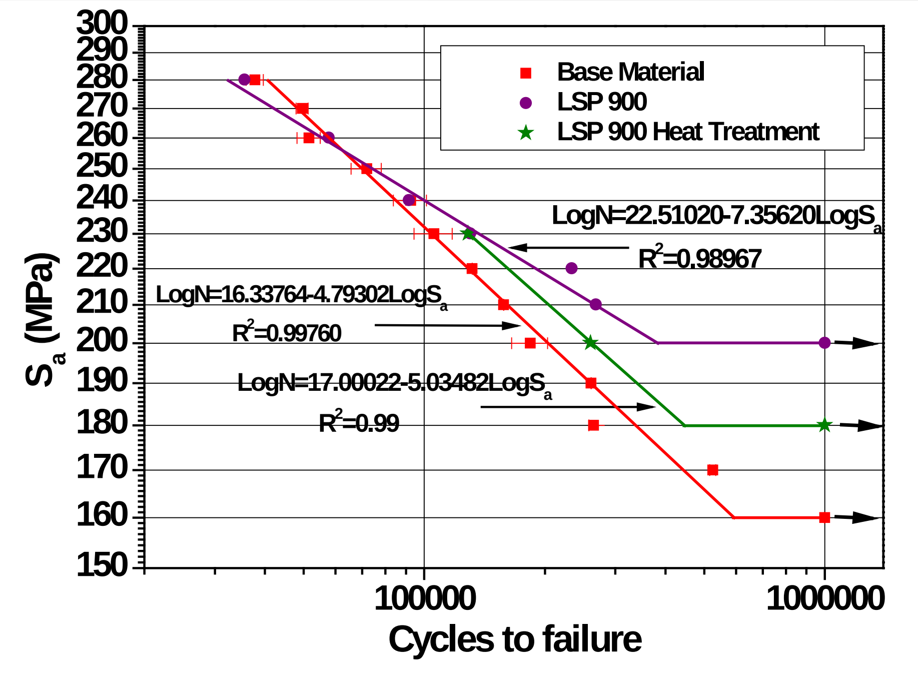
AISI 316L Stainless Steel + LSP 900 + LSP 1600 pulses/cm²					
S_a (Mpa)	S_{max} (Mpa)	F_{max} (kN)	F_{mean} (kN)	Cycles 900	Cycles 1600
280	622	54.507	29.979	**35574**	60199
260	578	50.613	27.837	**57777**	75105
240	533	46.720	25.696	**91471**	107098
230	511	44.773	24.625	**130302**	165560
220	489	42.827	23.555	**233301**	185802
210	467	40.880	22.484	**268180**	444006
200	444	38.933	21.413	**1000000**	1000000



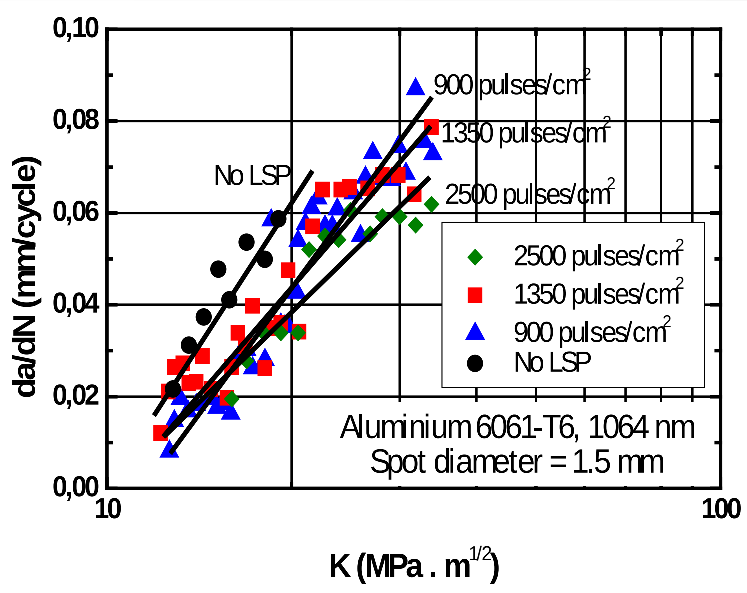
EXPERIMENTAL RESULTS

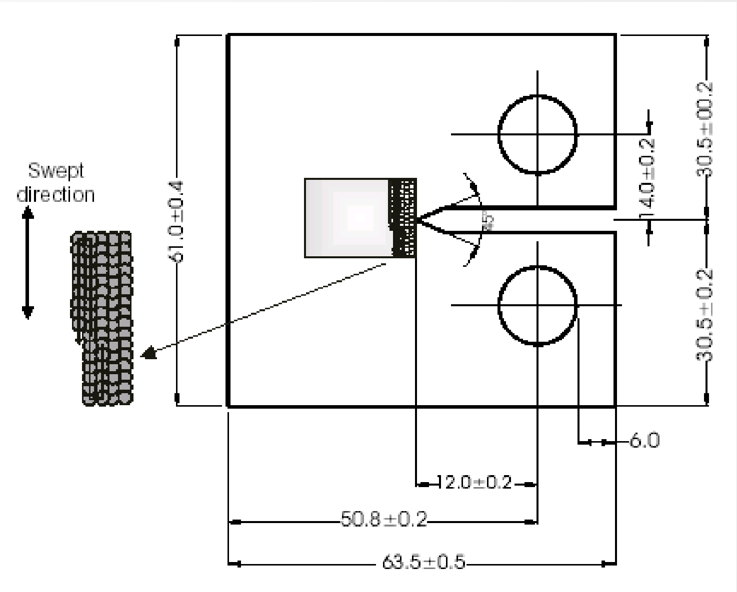
Fatigue Tests:

LSP 900 + Heat treatment (500ºC; 8h)				
S_a (Mpa)	S_{Max} (Mpa)	F_{max} (kN)	F_{mean} (kN)	Cycles
280	622	54.507	29.979	**6000**
230	511	44.773	24.625	**128632**
200	444	38.933	21.413	**259987**
180	400	35.040	19.272	**1000000**



EXPERIMENTAL RESULTS





$$\frac{da}{dN} = C.K^{m}$$

Pulse density (cm^{-2})	C (mm/cycle)	M (dimensionless)
0 (No LSP treatment)	4×10^{-13}	7.664
900	8×10^{-13}	6.818
1350	2×10^{-11}	5.733
2500	3×10^{-10}	4.723

Rubio-González, C. et al.: Mat. Sci. Eng. A., 386 (2004) 291-295

DISCUSSION AND OUTLOOK

A typical prospective LSP application to welding technology

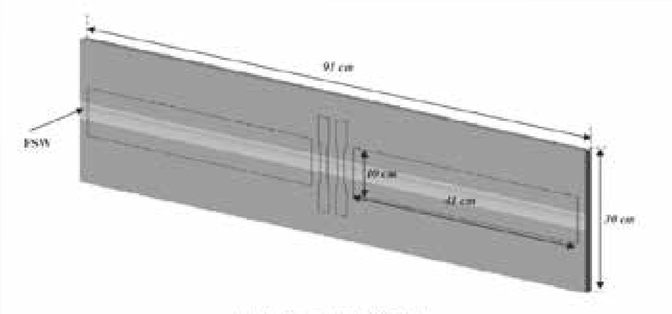


Fig. 3. Dimensions of the FSW plate.

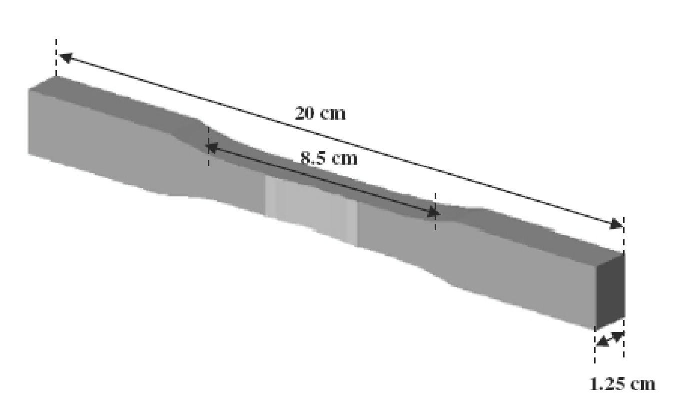
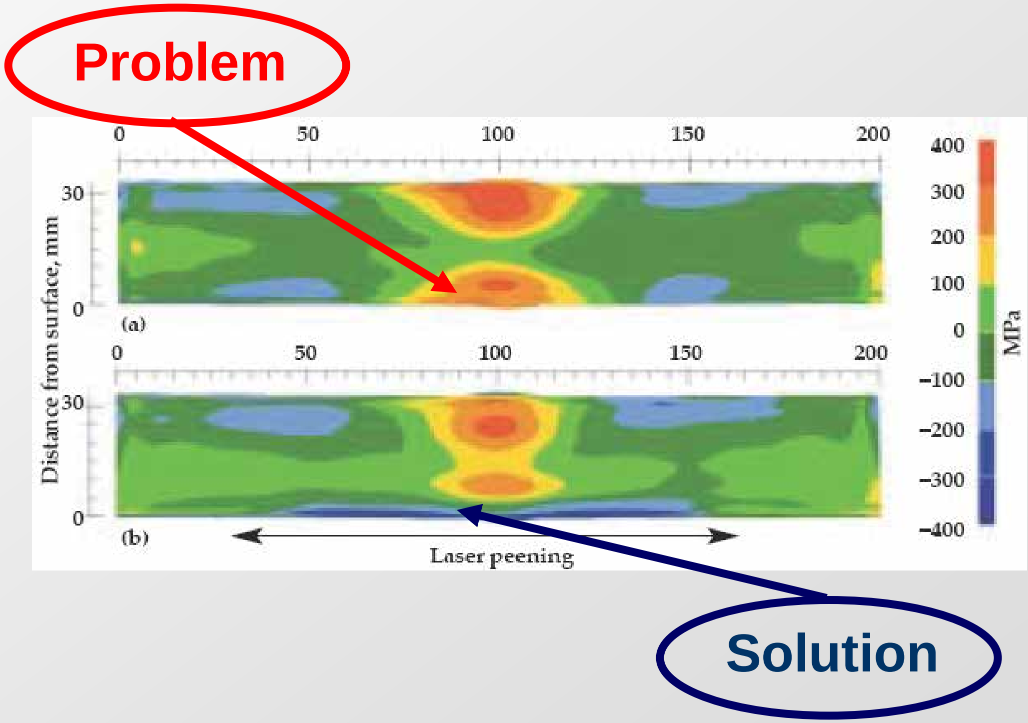
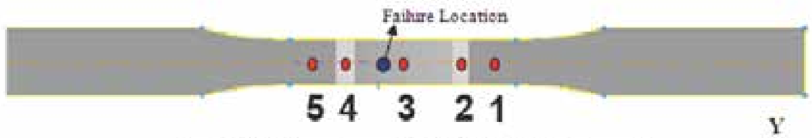


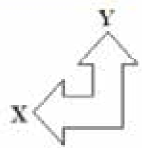
Fig. 4. Dimensions of the tensile specimen.



DISCUSSION AND OUTLOOK



Location 1	HAZ *(Advancing Side)*
Location 2	TMAZ *(Advancing Side)*
Location 3	Weld Nugget
Location 4	TMAZ *(Retreating Side)*
Location 5	HAZ *(Retreating Side)*



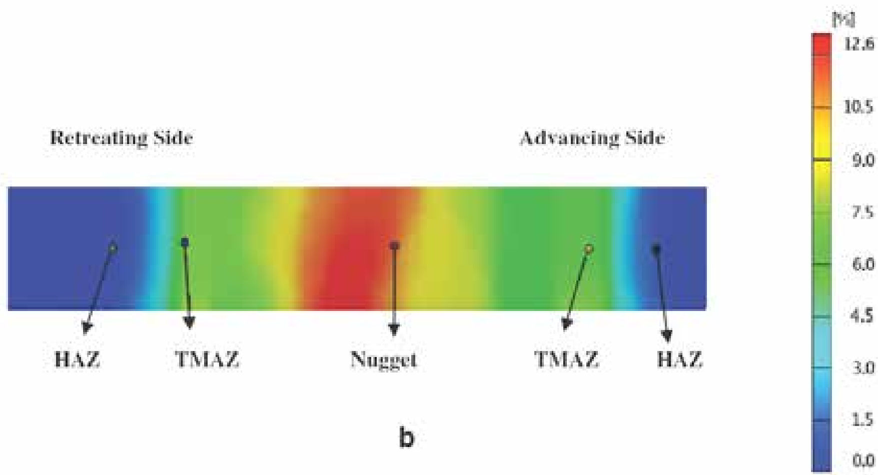


Fig. 10. (a) Tensile properties at different regions of the weld (b) Strain fields in the x-direction for the specimen before failure.

O. Hatamleh / **International Journal of Fatigue 31 (2009) 974–988**

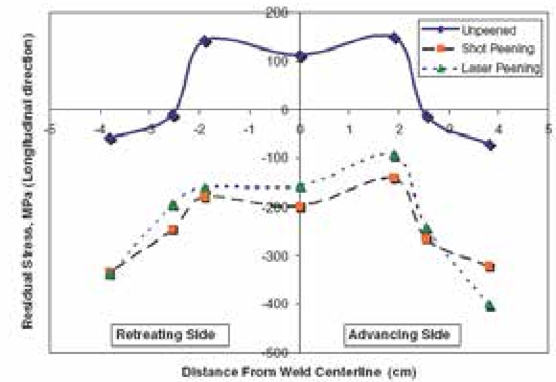


Fig. 11. Residual stresses for the various peened FSW specimens.

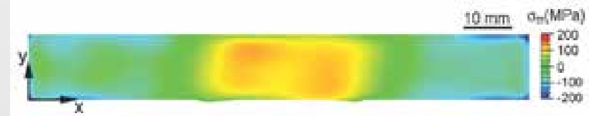


Fig. 12. Two-dimensional map of the measured residual stress for the unpeened FSW specimen.

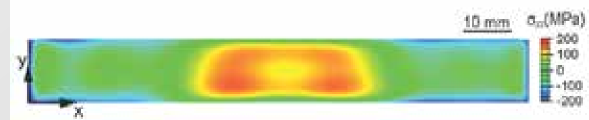


Fig. 13. Two-dimensional map of the measured residual stress for the shot peened FSW specimen.

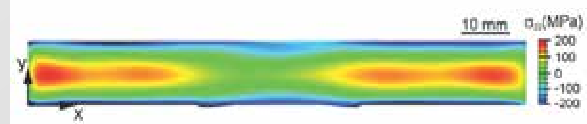
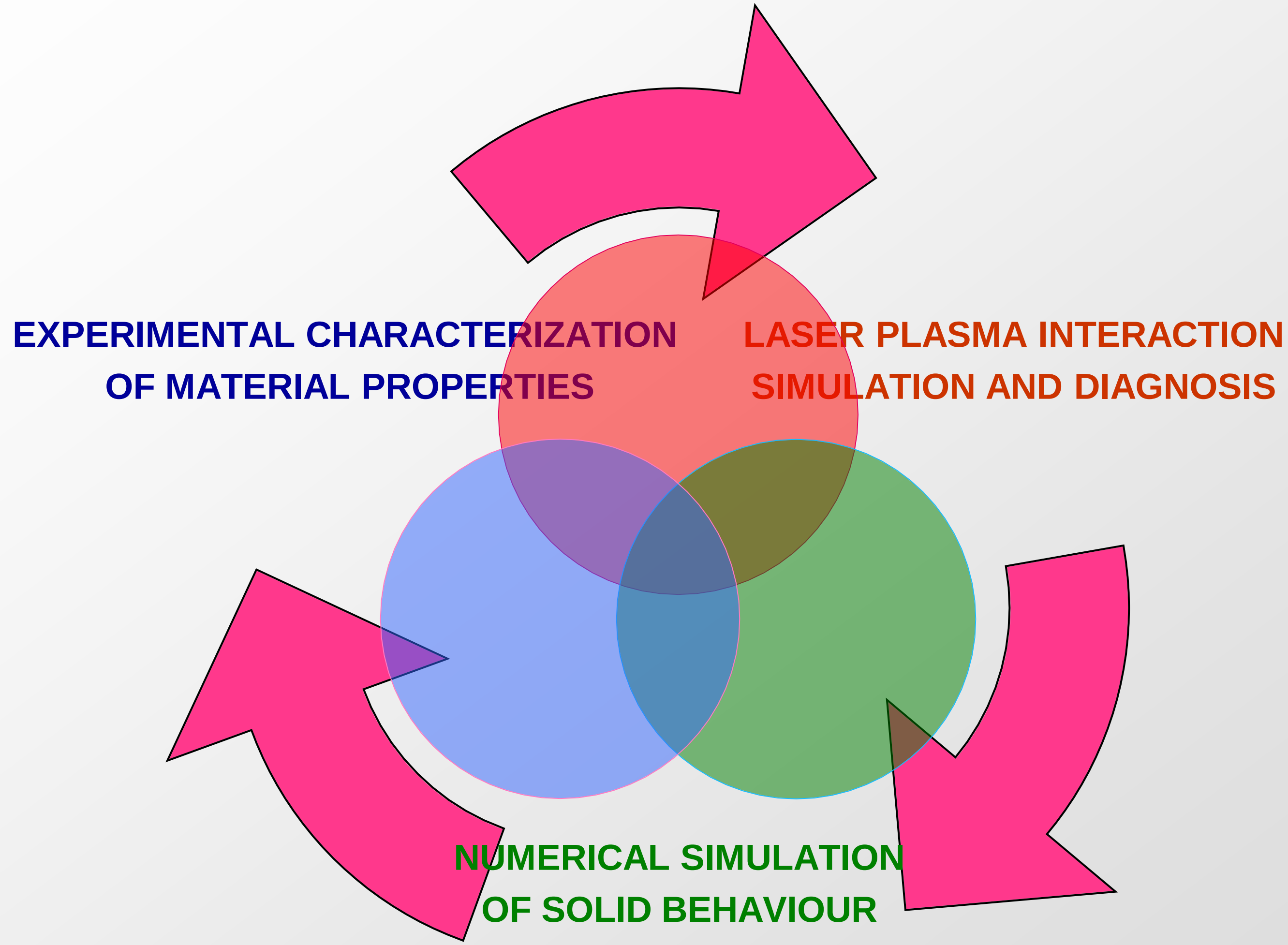


Fig. 14. Two-dimensional map of the measured residual stress for the laser peened FSW specimen.

DISCUSSION AND OUTLOOK

- **With the aid of the experimental irradiation and process diagnosis system implemented at CLUPM (Spain), a complete feasibility of the LSP technique at laboratory scale for the induction of improved material surface properties has been accomplished. The implementation of the appropriate experimental diagnosis methods enables a reliable process predictive assessment capability in view of process industrial implementation.**
- **The need for a practical capability of LSP process control in practical applications has led to the joint development of comprehensive theoretical/computational models and related material properties characterization capabilities able to properly assess the complex material issues arising in the process.**
- **With the aid of the developed experimental testing capability, a specifically targeted analysis of LSP induced effects (such as surface morphology, surface composition transformations, surface mechanical behaviour, deep residual stress fields and others) is made possible, thus allowing a practical development of the technique from an industrial point of view.**
- **Representative applications of the LSP technique to the treatment of typical aeronautic grade alloys (typically Al and Ti) and stainless steels characteristic of the aerospace, nuclear, biomedical and equipment industries, as well as to the post-treatment of welded metallic joints have been successfully conducted to the induction of compressive residual stresses fields decisively improving their fatigue life.**
- **Taking into account the benefits on the life extension side and the prospects for substitution of competing environmentally aggressive technologies, LSP is to be considered as a sustainability enabling technique.**

DISCUSSION AND OUTLOOK



ACKNOWLEDGEMENTS

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LSP: An emerging industrial technology

LSP: An Emerging Sustainability Supporting Technology

Next event on LSP:

4^{th} International Conference on Laser Peening and Related Phenomena

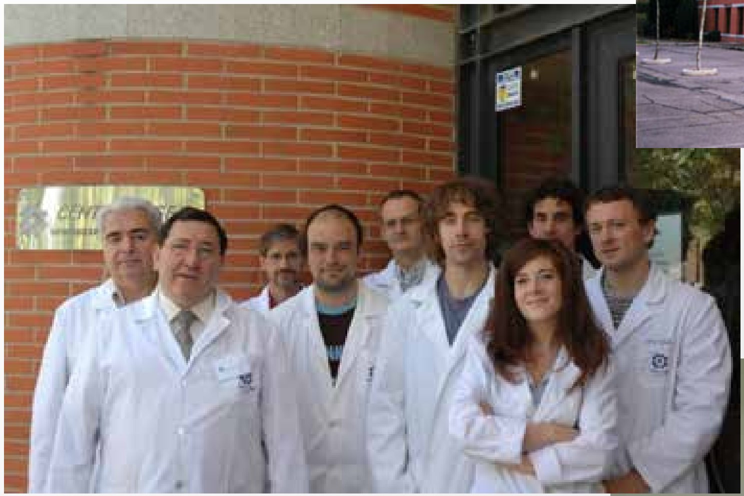
May 6^{th}-10^{th} 2013

ETS de Ingenieros Industriales, Universidad Politécnica de Madrid, SPAIN

Contact: jlocana@etsii.upm.es

http://www.upmlaser.upm.es/4-ICLPRP

The LSP Team at UPM Laser Centre



Thank you very much for your attention !

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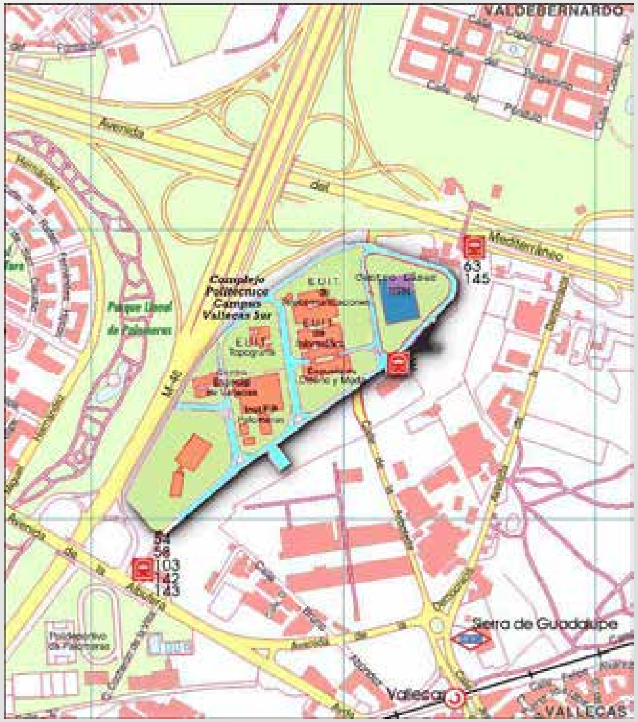
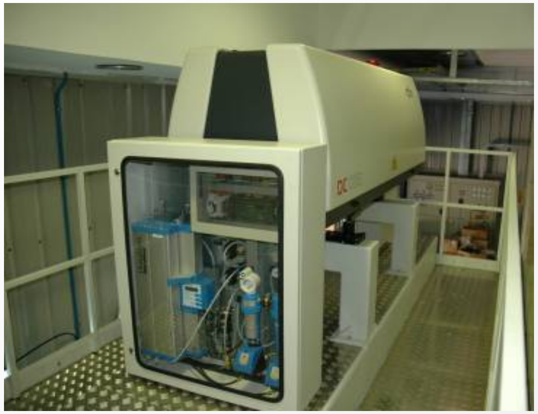
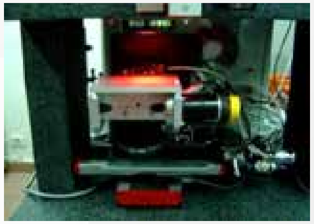


Major Facilities (1/4)

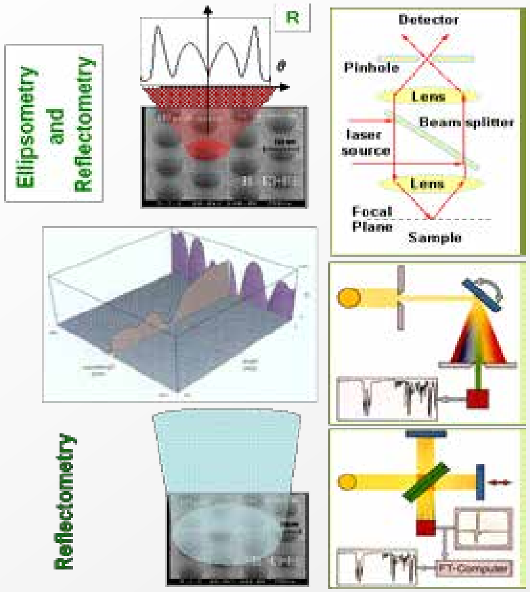


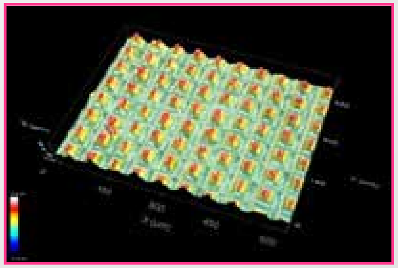
Major Facilities (2/4)

Major Facilities (3/4)



Major Facilities (4/4)





The SHOCKLAS Calculational System